NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3563

HEAT LOSS FROM YAWED HOT WIRES AT SUBSONIC MACH NUMBERS

By Virgil A. Sandborn and James C. Laurence

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

Heat-loss data at angles of yaw and fixed subsonic Mach numbers for several wires of different diameters commonly used in hot-wire anemometry are presented. Possible methods of correlating the data are examined. The relation of the Reynolds number normal to the flow, which has been used by most researchers, was inadequate except near a Mach number of zero. An empirical relation based on the weighted addition of the heat losses of normal and parallel wires correlated all data reasonably well.

INTRODUCTION

The study of heat loss from yawed circular cylinders is of general importance in aerodynamics, especially in hot-wire anemometry. The use of hot-wire anemometers to measure all the fluctuating components of a turbulent velocity field requires operation of two-wire probes, where the wires are usually arranged in directions other than normal to the flow. Thus, the relation between heat loss and angle of flow over the wire must be known in order to evaluate the turbulent velocities.

Schubauer and Klebanoff (ref. 1) obtained data at low speeds (approximately 100 ft/sec) which indicated that the variation of heat loss with flow angle was a linear function of the Reynolds number normal to the wire hereinafter referred to as the normal Reynolds number. The normal Reynolds number relation appeared to hold for angles of yaw greater than 20° (by definition, a wire parallel to the flow is at zero yaw, while a normal wire is yawed 90°). However, Newman and Leary (ref. 2) found that this relation was inadequate to represent their data. For their data, a heat-loss variation of the same form as Schubauer and Klebanoff's, but weighting the angle variation differently, was determined. The measurements of Newman and Leary were for a limited range of flow conditions and only one wire diameter.

The present investigation was initiated at the NACA Lewis laboratory to determine the heat loss from yawed hot wires over a wide range of subsonic flow conditions and for a number of wire diameters. A previously proposed and a new empirical correlation of the data are evaluated with regard to range of validity and usefulness.

APPARATUS AND PROCEDURE

Test facility. - Measurements for determining heat loss were made in the cone of an enclosed variable-density free jet, shown in figure 1. For the present tests, the Mach number was varied from approximately 0.2 to 0.9. The value of the Mach number was determined from static-pressure measurements at the jet-nozzle exit and total-pressure measurements (0 to 40 lb/sq in.) in the settling tank. The nozzle of the jet was $2\frac{3}{4}$ inches in diameter. Wires were located along the centerline of the jet approximately 2 inches downstream of the jet exit. The intensity of turbulence at this point varied from approximately 0.2 to 0.8 percent for the range of flows considered. 3658

Hot-wire probes and wires. - Figure 2 shows the dimensions of the two types of probe head used. The probe prongs were made of Inconel. Probes were mounted in a manner that permitted rotation about their centerline through an angle of 180° (see fig. 1(b)). Actuator rotation could be determined to 0.1°; however, initial alinement of the wires probably limited the accuracy of the angle of yaw to ±0.5°. The angle of yaw was measured with reference to the jet centerline.

Wires of 0.00116-, 0.00040-, and 0.000199-inch diameter were used in the experiments. The 0.00116- and 0.00040-inch-diameter wires were of 80 percent platinum - 20 percent iridium alloy. The 0.000199-inch-diameter wire was of drawn-etched tungsten. The 0.00116-inch-diameter wire was measured directly with an optical comparator and the diameter of the 0.000199-inch wire was determined from measurements with an electron microscope (ref. 3). The 0.00040-inch diameter was the value obtained from weight and resistance measurements stated by the manufacturer of the wire.

The platinum-iridium wires were silver soldered directly to the probe prongs. The tungsten wire was copper plated at its ends and soft soldered to the prongs. The unplated section of tungsten wire was approximately 0.080 inch long. The platinum-iridium wires were approximately 0.1 inch in length. All lengths were determined with a traveling microscope.

Electrical equipment. - The wires were operated at a constant mean resistance by a semiautomatic self-balancing Kelvin bridge. This type of bridge was used in order to minimize errors due to lead and contact resistance. The bridge was set to maintain operating resistance of the hot wires corresponding to wire temperatures of 750° F for the platinum-iridium wires and 570° F for the tungsten wires. The wire current was determined by measuring the potential drop across a 1-ohm precision resistor.

Flow setup. - Pressures were measured to three significant figures on both water and mercury manometers. Some uncontrollable fluctuations occurred in the inlet-air supply, which may have resulted in a random error in the reading of the third significant figure. The total temperature in the settling tank was read to the nearest degree and did not appear to be affected by the pressure fluctuations. Flow parameters other than Mach number were calculated to three significant figures.

Support interference. - Measurements were made with wires mounted on two different probe heads (fig. 2) in order to check support-interference effects. Corresponding heat losses from the two probes are shown in figure 3. Any differences in heat loss, except near zero angle of yaw, appear to be random. Probably at zero angle of yaw the supports of both probes interferred with the flow along the wire. However, it was impossible to determine any support interference corrections, since the heat-loss values obtained with the two shapes used were in agreement.

Heat-loss calculations. - For all measurements, the resistance of the wire was corrected to account for the known resistance of the support. This correction reduced the cold resistances measured by about 16 percent for the 0.00116-inch-diameter wire, 2 percent for the 0.00040-inch-diameter wire, and 4 percent for the 0.000199-inch-diameter wire. The cold resistance of any given wire changed slightly (by not more than 2 percent) during a day's operation. It was possible to correct for this error if the wire resistance could be measured after a run.

The accuracy of the heat-loss calculations appeared to be limited by the drift in wire resistance. This drift may have caused some systematic error that could affect the third significant figure of the resistance. Wire current was read to four significant figures.

RESULTS AND DISCUSSION

The average heat loss from small circular wires is known to be affected by the following factors: (1) Reynolds number, (2) Prandtl number, (3) Mach number, (4) angle of yaw, (5) wire diameter, (6) wire length, (7) temperature loading, and (8) turbulence. The heat loss may be expressed nondimensionally by a Nusselt number

$$\mathrm{Nu} = \frac{Hd}{k} \tag{1}$$

(A list of symbols is given in the appendix.) For hot-wire measurements, the Nusselt number is generally expressed as

$$\mathrm{Nu} = \frac{i^2 R}{\pi l k \Delta t} \tag{2}$$

The relation of Nusselt number to the variables listed may be expressed as

$$\mathrm{Nu} = f\left(\mathrm{Re}, \mathrm{Pr}, M, \psi, \frac{l}{d}, \Delta t, \frac{\sqrt{\overline{u^2}}}{U}\right) \tag{3}$$

In the present investigation, the variation of heat loss Nu with angle of yaw ψ was determined for a range of Mach numbers M and Reynolds numbers Re. The effect of aspect ratio l/d was evaluated for wires normal to the stream. The Prandtl number Pr was assumed constant. Temperature-loading Δt effects have been determined in references 3 to 6, and were not considered in the present set of data. The turbulence intensity of the jet $\sqrt{\overline{u^2}}/U$ was so low that it was not considered to influence the measurements.

Heat Loss from Wires Normal to Flow

The dependency of heat loss on Reynolds number for wires normal to the flow has been established as

$$\mathrm{Nu} = A\sqrt{\mathrm{Re}} + B \tag{4}$$

The values of thermal conductivity and viscosity in the expression for Nu and Re are for film temperature, defined as arithmetic mean of the cold-wire recovery temperature (ref. 4) and the heated wire temperature. Mass flow rate ρU is the free-stream value. The slope A and intercept B depend on the other parameters governing the heat loss.

Aspect ratio. - The effect of wire diameter and length may be combined nondimensionally as l/d, the aspect ratio of the wire. Figure 4(a) shows the results of heat-loss measurements with three wires of different aspect ratios at a Mach number of 0.2. Examination of the data after end-loss corrections are made shows no effect of aspect ratio on the heat loss from the wires. These corrections for heat conduction to the wire supports were made by the method outlined in reference 4. (A different correction was used in refs. 5 and 6, but was found to give substantially the same result.)

The magnitude of the end-loss corrections can be inferred by comparing figures 4(a) and (b). Figure 4(a) shows the uncorrected data
3658 for the three wire diameters, while figure 4(b) shows the same data with end-loss corrections. The slopes A of equation (4) for wires normal to the flow direction and of different aspect ratio agree within the repeatable accuracy of any one wire; and for a given Mach number, the data correlate into a single curve after end-loss corrections are applied. Hence, the end-loss corrections eliminate aspect ratio as a variable for normal wires. This correction was assumed adequate for yawed wires also. This is equivalent to assuming that conduction into the prongs is independent of yaw angle.

Mach number. - The variation of heat loss with Reynolds number for normal wires at fixed Mach numbers is shown in figure 5. The variation with Mach number is similar to that observed in references 3 to 5. A summary of the slopes A for the different wires is shown in figure 6. A linear approximation to the data of figure 6 is given by the following relation:

$$A = 0.459 - 0.154M \tag{5}$$

The value of the intercept B of equation (4) cannot be reliably determined from the data available as is evident from a comparison of figures 5(a) and (b).

Flow regime. - Because of the small wire diameter and the low densities for Mach numbers approaching 1, the wires may be operating in a regime of slip flow. For slip flow the ratio of the molecular mean free path of the fluid to the wire diameter (Knudsen number) must be considered as an additional parameter. As suggested in reference 5, the variation of Knudsen number can be expressed as a variation of the density of the fluid. From kinetic theory the mean free path is found to be inversely proportional to the density (this relation assumes that the diameter of the molecules does not vary with temperature)

$$\frac{1}{Kn} = \frac{d}{\lambda} = \text{constant} \times \rho d$$

The constant given by reference 5 was used to determine the variation of heat loss with $\sqrt{d/\lambda}$ at fixed Mach numbers, which is shown in figure

7. The regime of slip flow is usually defined as $d/\lambda < 100$. Some of the points for the 0.00040- and 0.000199-inch-diameter wires fall in the slip-flow region.

In reference 7 the parameter $\frac{M}{Re\ Pr}$ was found to correlate measurements at several Mach numbers in the transonic range. Figure 8 is a plot of this parameter against Nusselt number for the present data, which also shows the mean curve of the data of reference 7 (the curve of ref. 7 is corrected to film temperature). The shift between the data of reference 7 and the present data may be due to a difference in temperature loading of the wire. The lack of correlation, however, indicates that the parameter $\frac{M}{Re\ Pr}$ is not significant in the range of variables of these tests.

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Heat Loss from Yawed Wires

The angle of yaw, as noted in figure 2, is the angle between the direction of mean flow and the axis of the wire. A wire parallel to the flow is at zero angle of yaw, while the yaw angle for a wire normal to the flow is 90°.

Figure 9 shows the variation of heat loss with Reynolds number at fixed angles of yaw for various Mach numbers and wire diameters. The solid curves drawn through the points are least-squares representations of the data. The constant A of equation (4) decreases as the wire is rotated parallel to the flow, indicating a function of ψ decreasing as ψ changes from 90° to 0°. The determination of the intercept B of equation (4) is unreliable for the data, since the Reynolds number range did not extend to values low enough to define the intercept.

As previously noted, reference 1 suggests that the yaw data could be correlated by the normal Reynolds number as follows:

$$Nu = A\sqrt{Re \sin\psi} + B \tag{7}$$

This law obviously must break down when the angle of yaw ψ approaches zero. The limits placed on this equation (in ref. 1) were that the angle of yaw should be greater than 20°. Figure 10 shows typical results of the data plotted according to equation (7). In general, the correlation is poor except perhaps at very low Mach numbers.

The authors of reference 2 also found disagreement with equation (7). They suggested modifying equation (7) to the form

$$Nu = A\sqrt{Re}\,(\sin\psi)^n + B \tag{8}$$

($n = 0.457$ for the data of ref. 2; Mach number ~ 0.05). Again equation (8) must be limited to some angle of yaw greater than zero. Correlations of this type are shown in figure 11. The values of n were computed by the method of least squares. The method was found to correlate the data for angles of yaw greater than approximately 10°. The values of n, however, show little systematic variation with Mach number (fig. 12). This method of correlating the data may be convenient in hot-wire anemometry, but has little generality, since it appears to require a separate experimental determination of the exponent n for each wire tested.

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An attempt was made to obtain a relation that would correlate the present data over the whole range of angles of yaw. A logical approach was to combine the known relation for heat loss from a normal wire, equation (4), with that of a parallel wire. Equation (4) with different constants

$$Nu = C\sqrt{Re} + D \tag{9}$$

was found to fit the parallel-wire data adequately.

When the heat loss from the parallel wire is considered as analogous to that from a flat plate, an equation of the form of equation (9) would be expected. Reference 8 derives the flat-plate equation, which is similar to equation (9) with $D = 0$. The analysis of reference 9, which treats the effect of curvature and that of reference 10, which deals with slip flow, both indicate the need for an additional constant, D.

From the data it was found that equation (9) with $D = 0$ could adequately represent the heat loss from the 0.00116-inch-diameter wires parallel to the flow, but the addition of the constant was required for the smaller wires.

The slopes C of the heat-loss curves for the parallel wires are plotted against Mach number in figure 13. The value of C is nearly independent of Mach number.

The following weighted combination of equations (4) and (9) was found to represent the data

$$Nu = (A\sqrt{Re \sin\psi} + B)\sin\psi + (C\sqrt{Re \cos\psi} + D)\cos\psi \tag{10}$$

The values A and B were evaluated from the normal-wire data, and C and D were evaluated from the parallel-wire data. (See figs. 6 and 13.)

Figure 14 shows the correlation of the data by equation (10). (The data for 0.00040-in.-diam. wire at $M = 0.9$ were insufficient to evaluate the constants.) In general, the correlation gives agreement within approximately 10 percent over the complete range of angle of yaw. However, the deviations of equation (10) from experimentally determined Nusselt numbers are systematic with angle rather than random, suggesting that equation (10) is still not the complete answer. Secondly, attempts to evaluate A, B, C, and D at angles other than 90° and 0° do not give reliable values.

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SUMMARY OF RESULTS

Results of this investigation of heat loss from yawed wires may be summarized as follows:

1. The effect of aspect ratio on the heat loss from wires normal to the flow can be eliminated by end-loss corrections.

2. The slope in the equation for heat loss from normal wires varied linearly with Mach number in the following form:

$$A = 0.459 - 0.154M$$

where A is the slope and M is the Mach number.

3. The use of Reynolds number normal to the flow to correlate heat-loss measurements at angle of yaw appeared adequate only near zero Mach number and angles of yaw greater than 20°.

4. The relation

$$Nu = A \sqrt{Re}\ (\sin \psi)^n + B$$

where Nu is the Nusselt number, Re is the Reynolds number, ψ is the angle of yaw, n is an arbitrary power, and B is a constant, may be empirically evaluated to correlate the heat-loss data for angles of yaw greater than approximately 10°. However, a systematic variation of n with Mach number or wire size was not found. The value of n must be determined from measurements for each wire operated.

5. The equation

$$Nu = (A \sqrt{Re \sin \psi} + B)\sin \psi + (C \sqrt{Re \cos \psi} + D)\cos \psi$$

obtained by combining the heat loss of wires normal and parallel to the flow correlated the data for all angles of yaw within approximately 10 percent. Deviations, however, were systematic rather than random, indicating a need for a still more accurate equation.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 12, 1955

APPENDIX - SYMBOLS

The following symbols are used in this report:

A,B	constants in King's equation
C,D	constants in parallel cylinder heat-transfer equation
C_p	specific heat at constant pressure
d	diameter of the wire
H	heat-transfer coefficient
i	wire heating current
Kn	Knudsen number, $\frac{\lambda}{d}$
k	thermal conductivity of air
l	wire length
M	Mach number
Nu	Nusselt number, $\frac{Hd}{k}$
n	exponent of sin ψ
Pr	Prandtl number, $\frac{C_p \mu}{k}$
R	wire resistance
Re	Reynolds number based on wire diameter, $\frac{\rho U d}{\mu}$
t_e	wire recovery temperature
t_w	wire temperature
U	mean longitudinal velocity
$\sqrt{\overline{u^2}}$	root mean square of longitudinal turbulent velocity
Δt	temperature loading, $t_w - t_e$
λ	molecular mean free path of air

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μ coefficient of viscosity

ρ density

ψ angle of yaw

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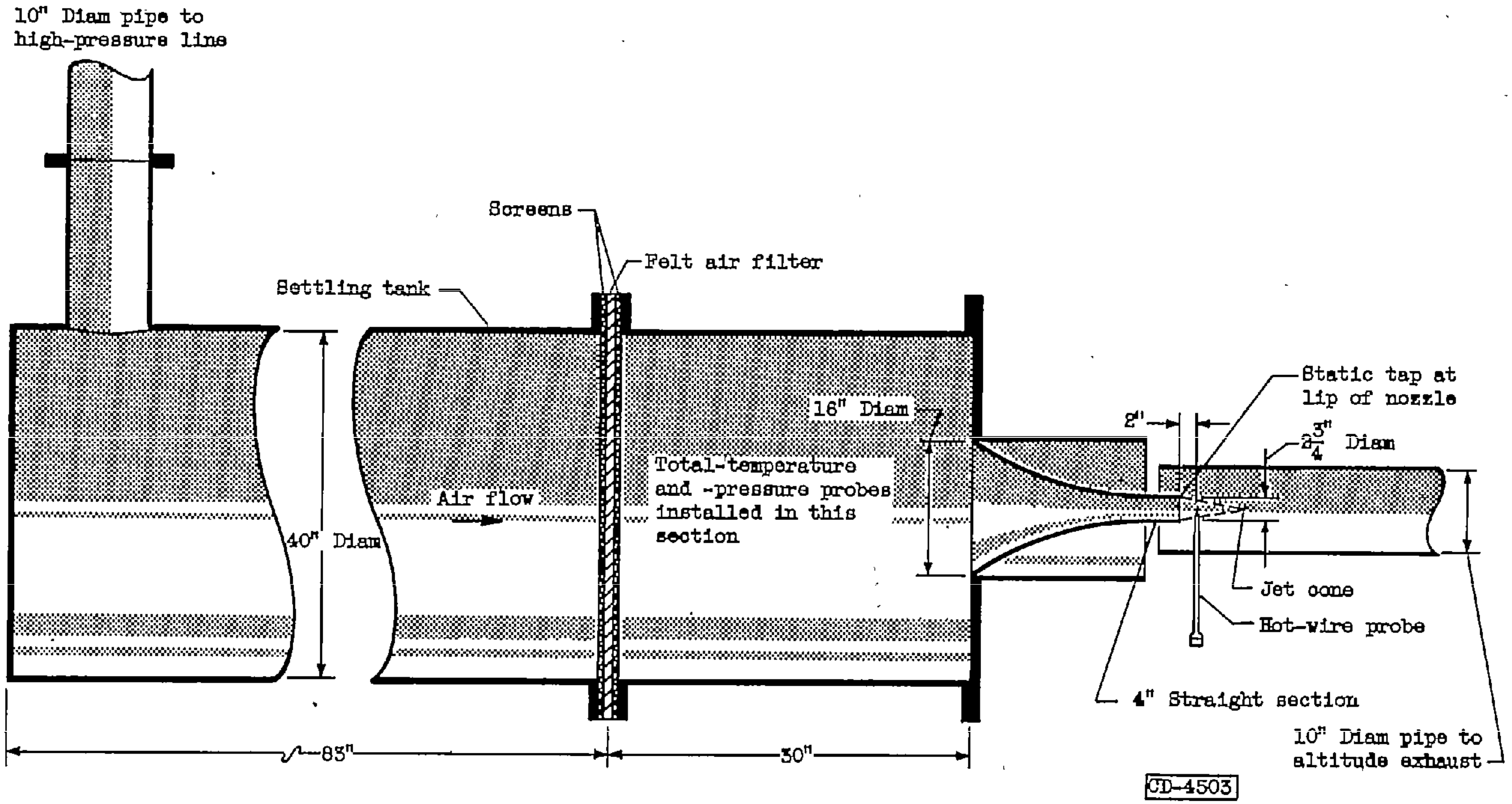

(a) Jet details.

Figure 1. - Variable subsonic Mach number and Reynolds number jet.

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(b) Probe mounted in jet.

Figure 1. - Concluded. Jet having variable subsonic Mach number and variable Reynolds number.

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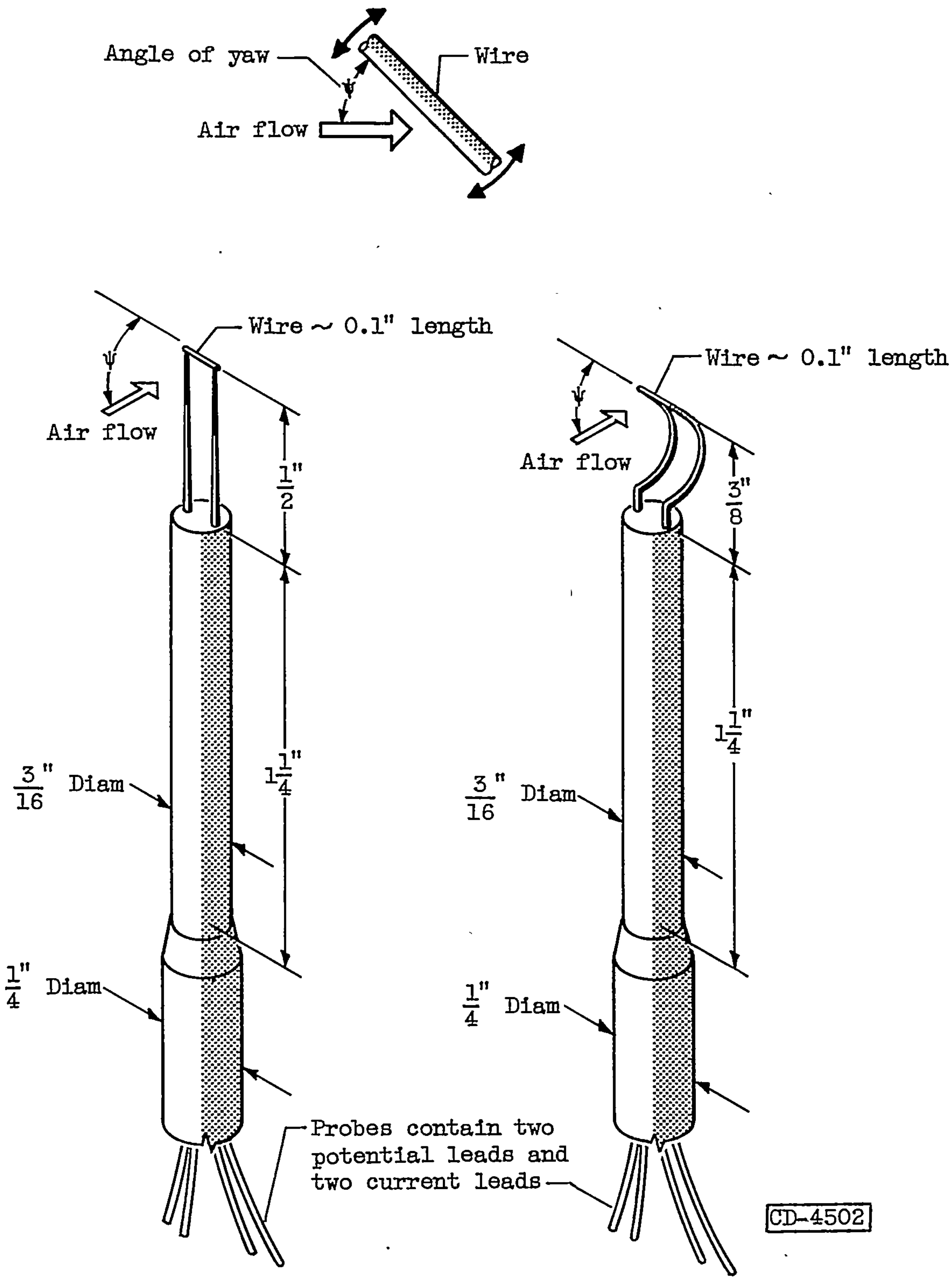


(a) Probe 1.

(b) Probe 2.

Figure 2. - Hot-wire probes showing prong geometry.

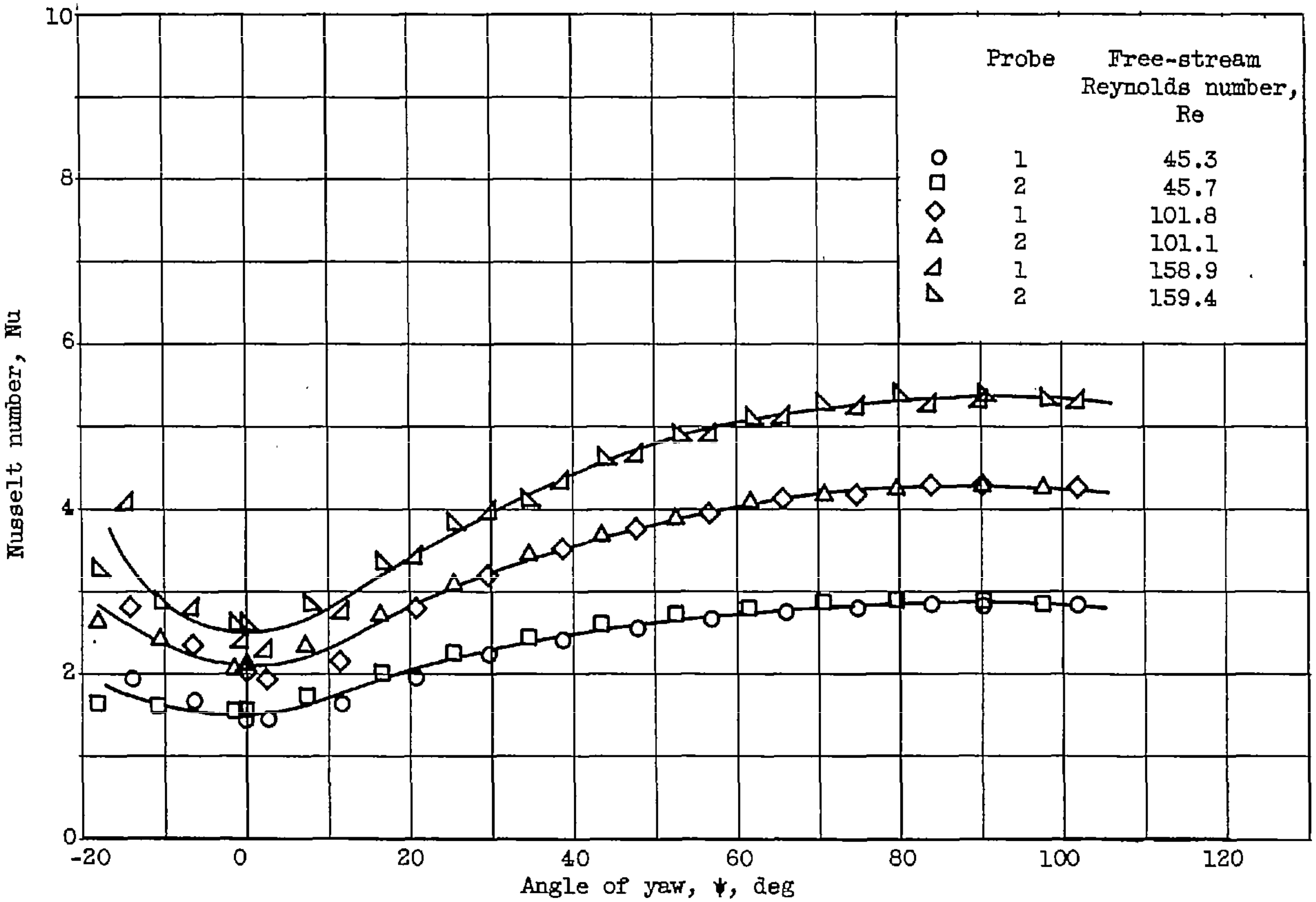
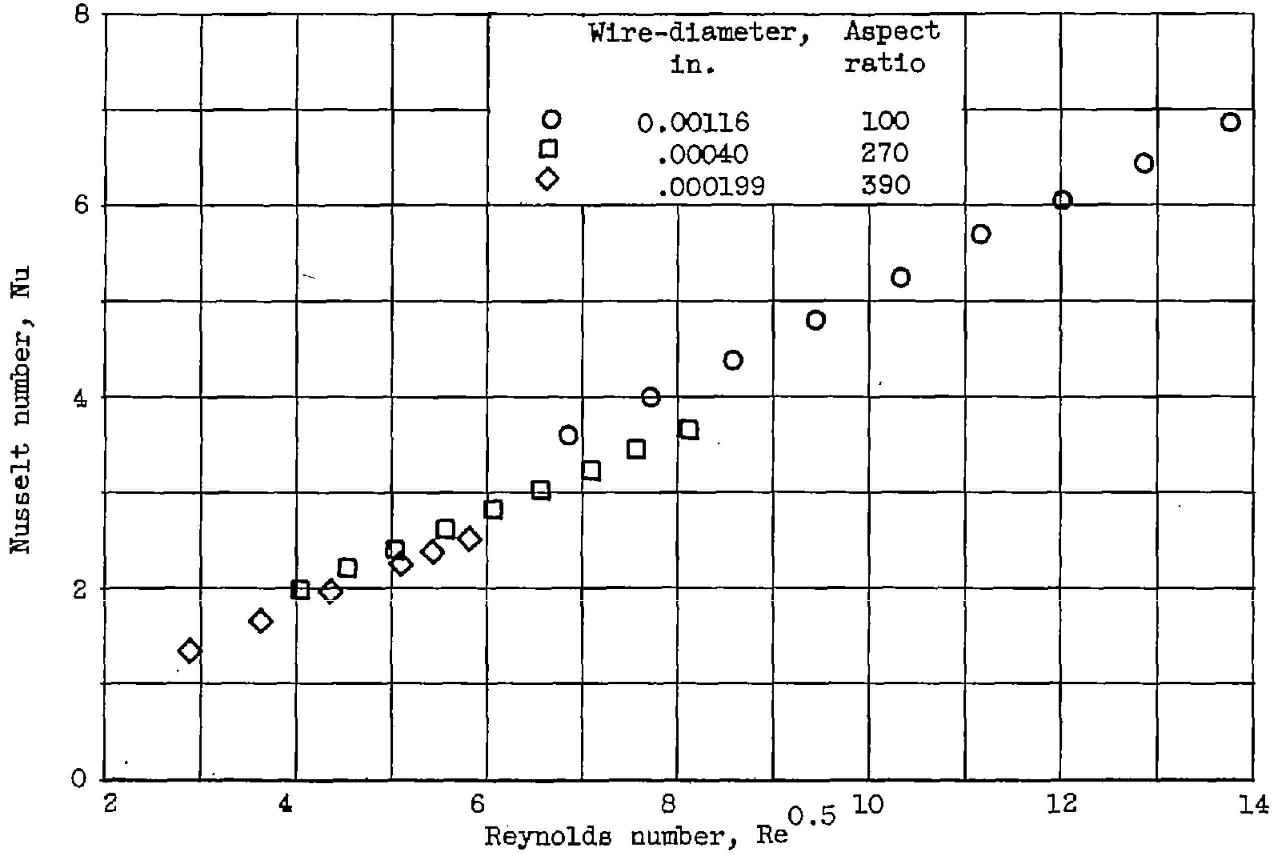
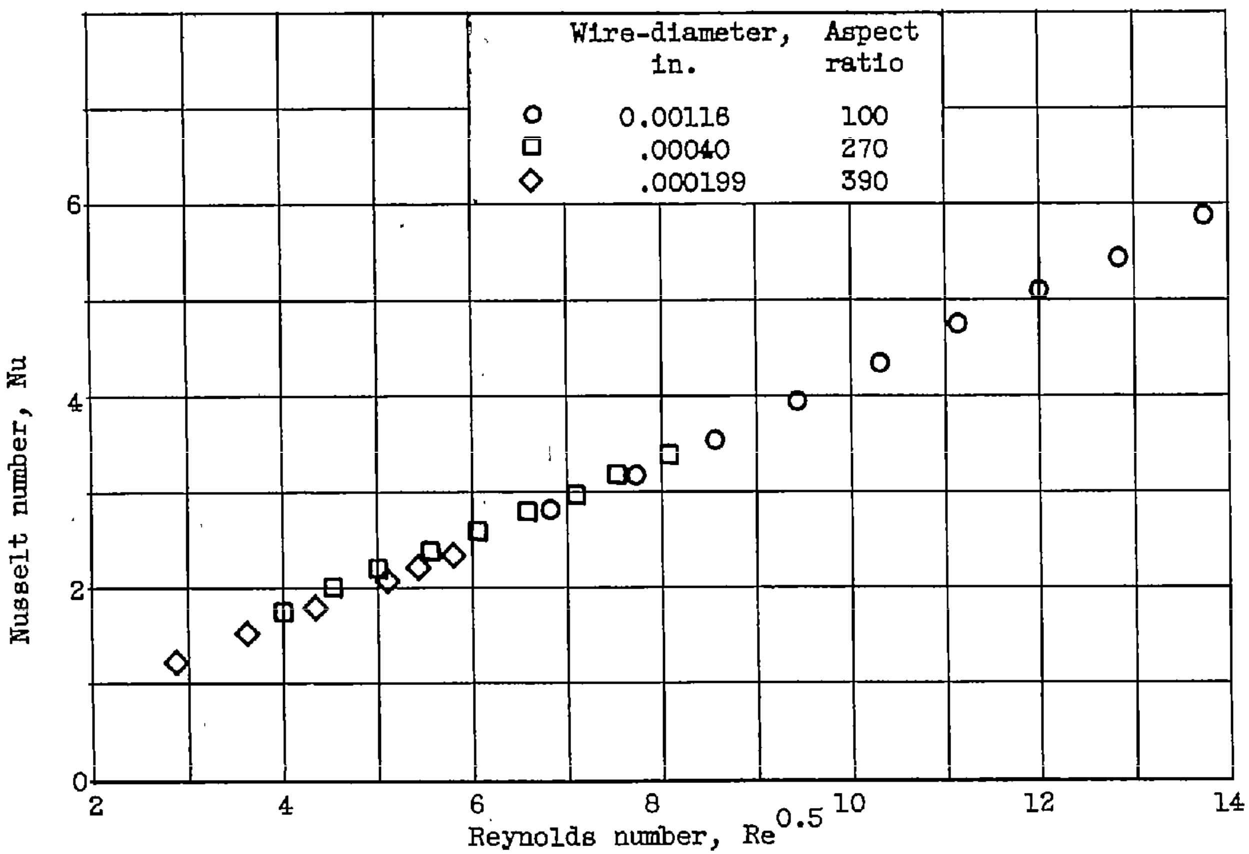


Figure 3. - Comparison of heat loss with angle of yaw for different probe geometry at a Mach number of 0.2. Platinum-iridium wire; diameter, 0.00116 inch.



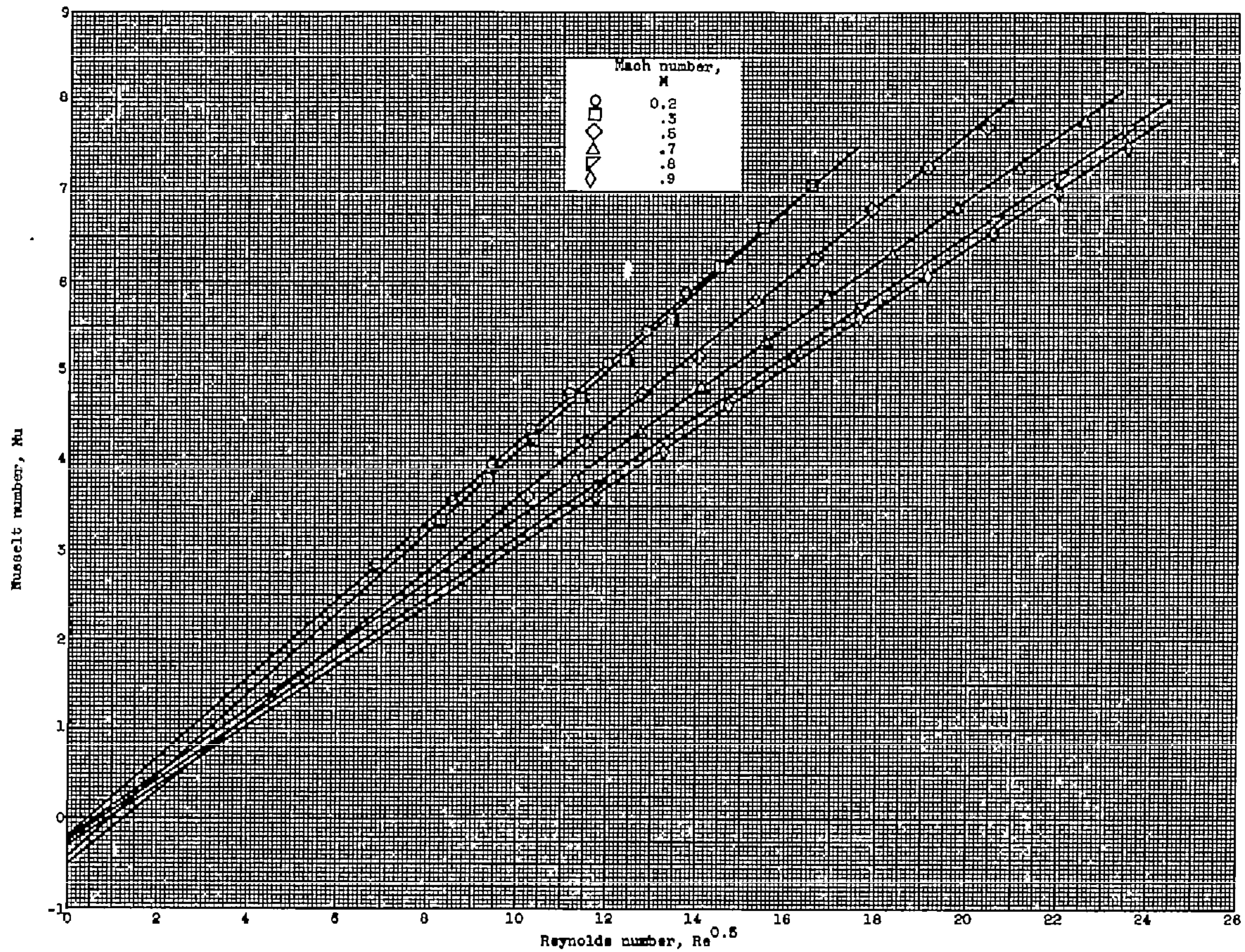
(a) No end-loss corrections.

Figure 4. - Variation of heat loss with Reynolds number for different wire diameters at Mach number of 0.2.



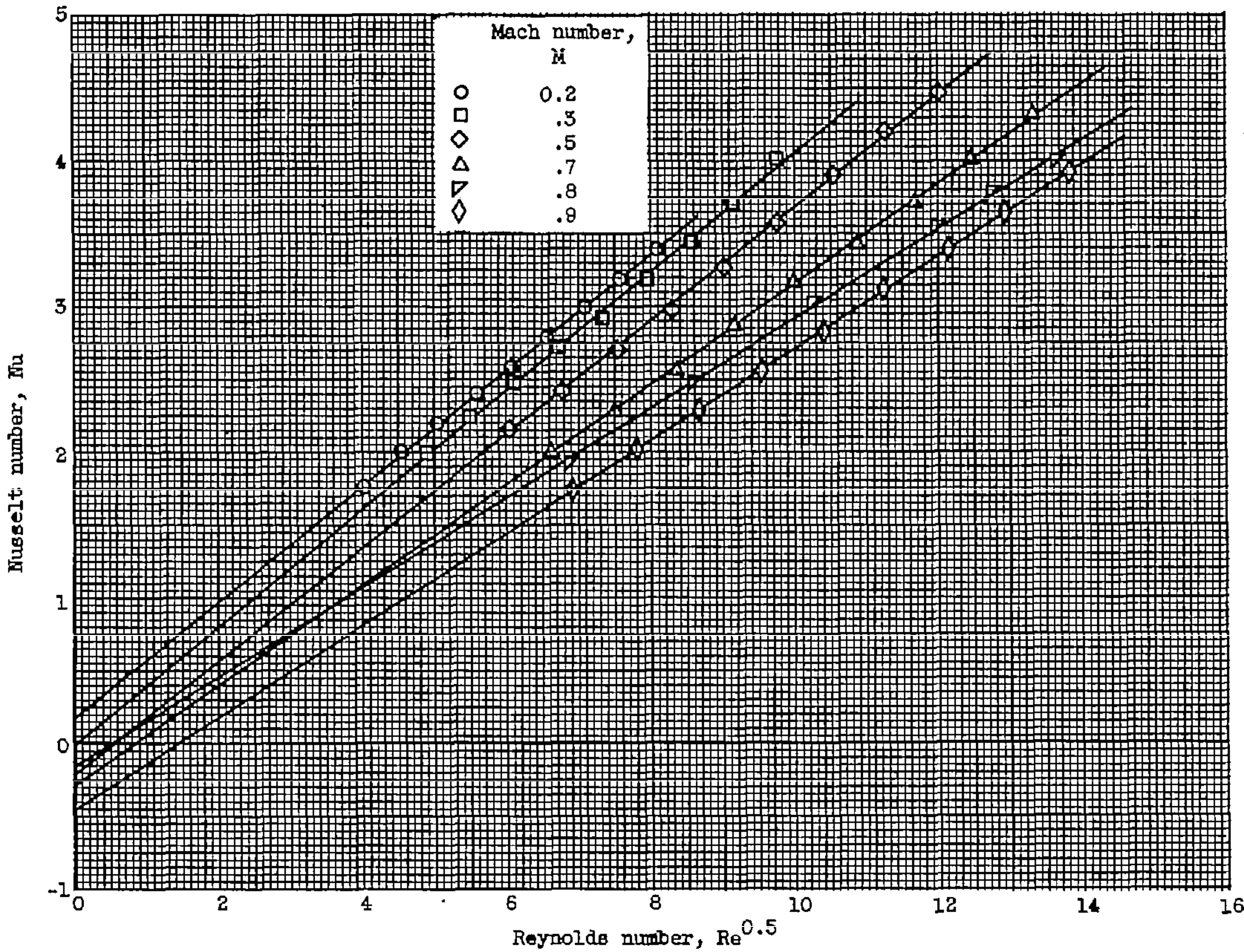
(b) End-loss corrections.

Figure 4. - Concluded. Variation of heat loss with Reynolds number for different wire diameters at Mach number of 0.2.



(a) Wire diameter, 0.00116 inch; aspect ratio, 100.

Figure 5. - Variation of heat loss with Reynolds number for a normal wire at various Mach numbers. Curves fitted by method of least squares.



(b) Wire diameter, 0.00040 inch; aspect ratio, 270.

Figure 5. - Concluded. Variation of heat loss with Reynolds number for a normal wire at various Mach numbers. Curves fitted by method of least squares.

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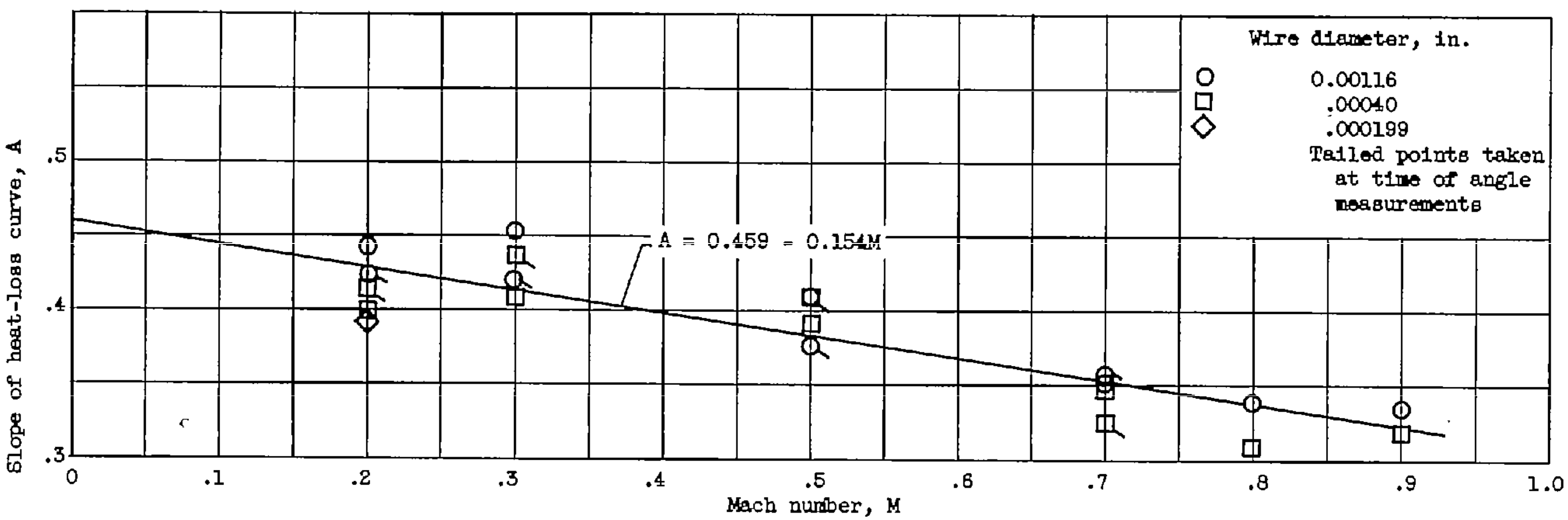
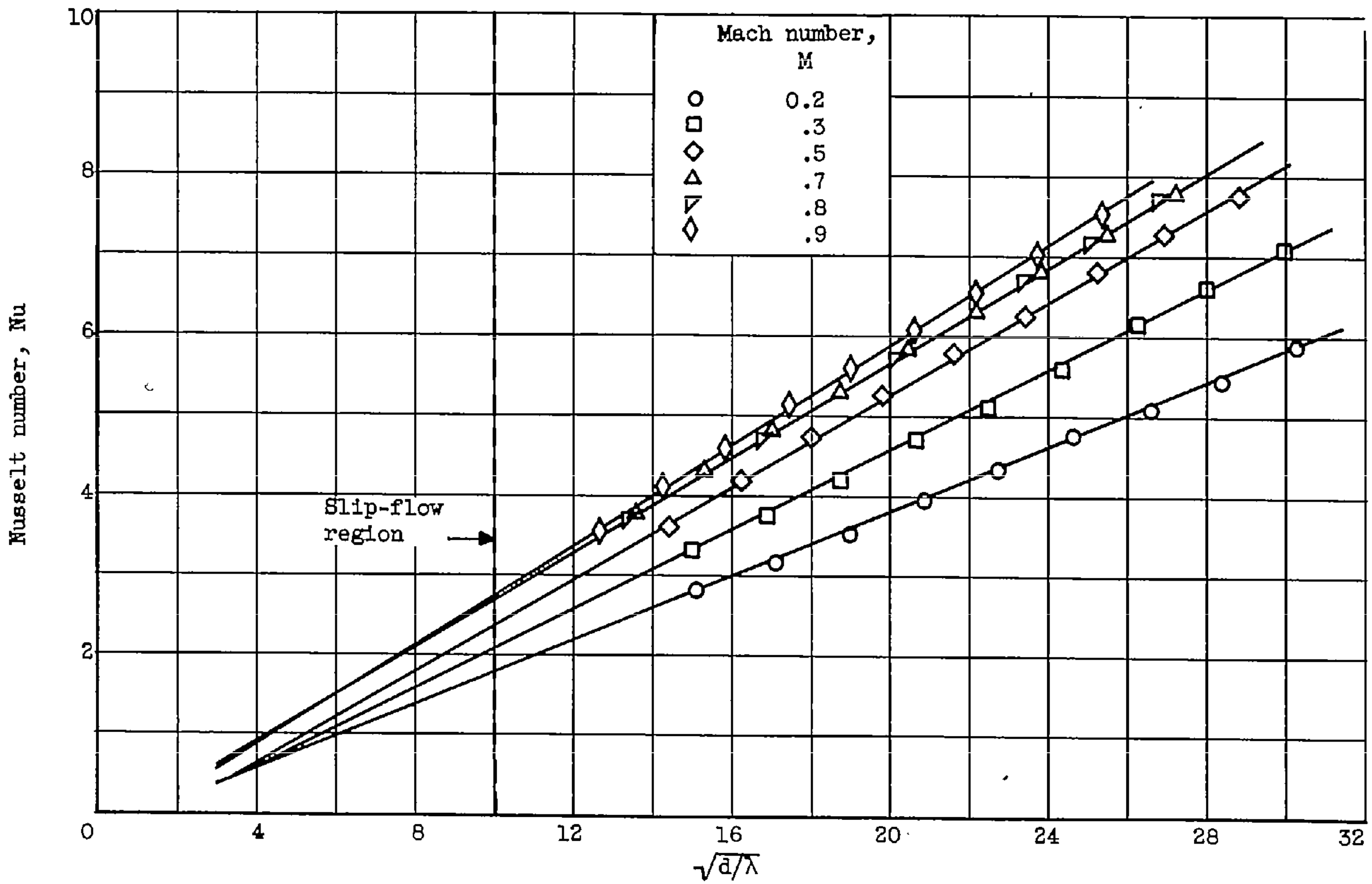
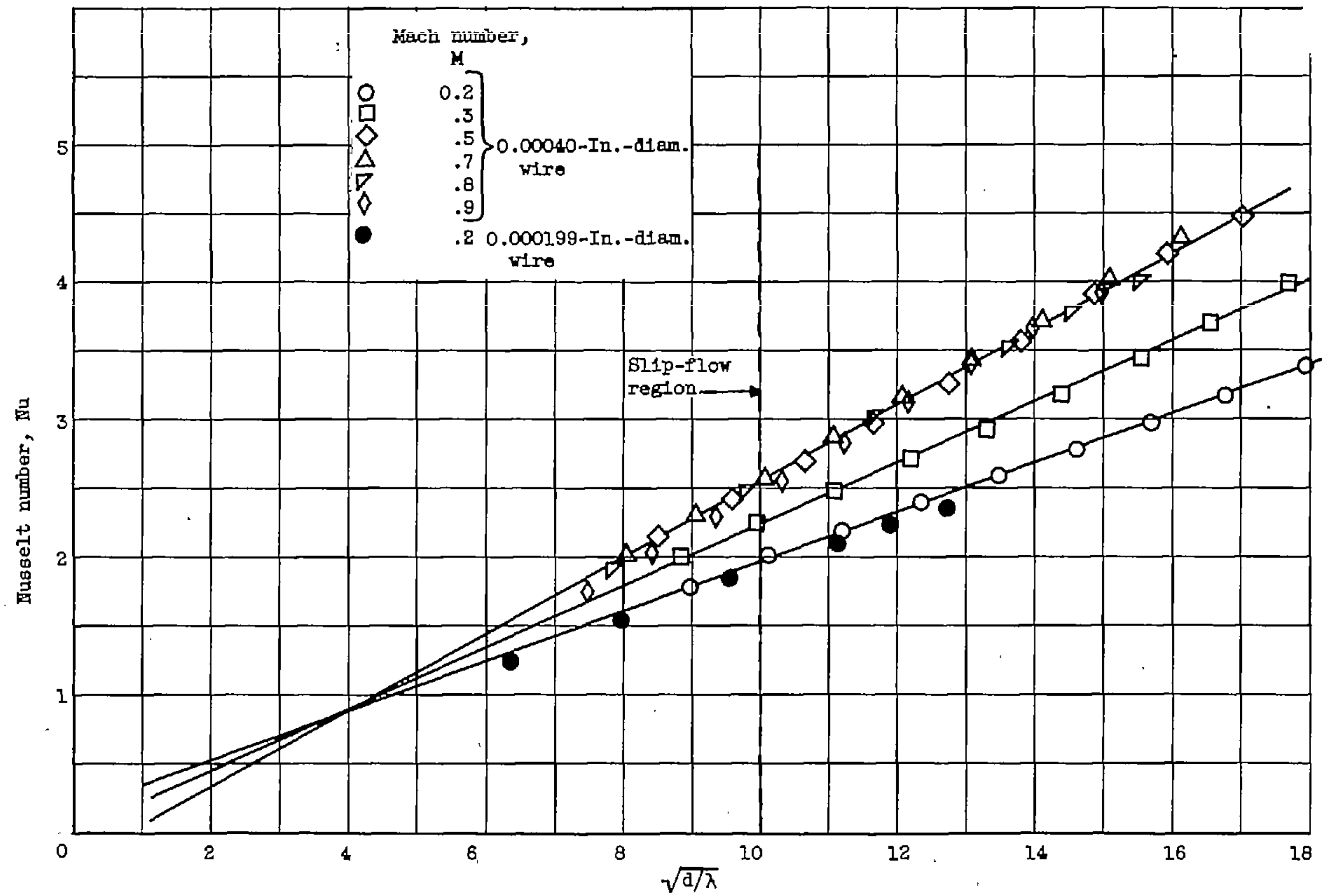


Figure 6. - Summary of slopes of heat-loss curves for normal wires at various Mach numbers.



(a) Wire diameter, 0.00116 inch.

Figure 7. - Variation of heat loss with slip-flow parameter for normal wires at various Mach numbers.



(b) Wire diameter, 0.00040 and 0.000199 inch.

Figure 7. - Concluded. Variation of heat loss with slip-flow parameter for normal wires at various Mach numbers.

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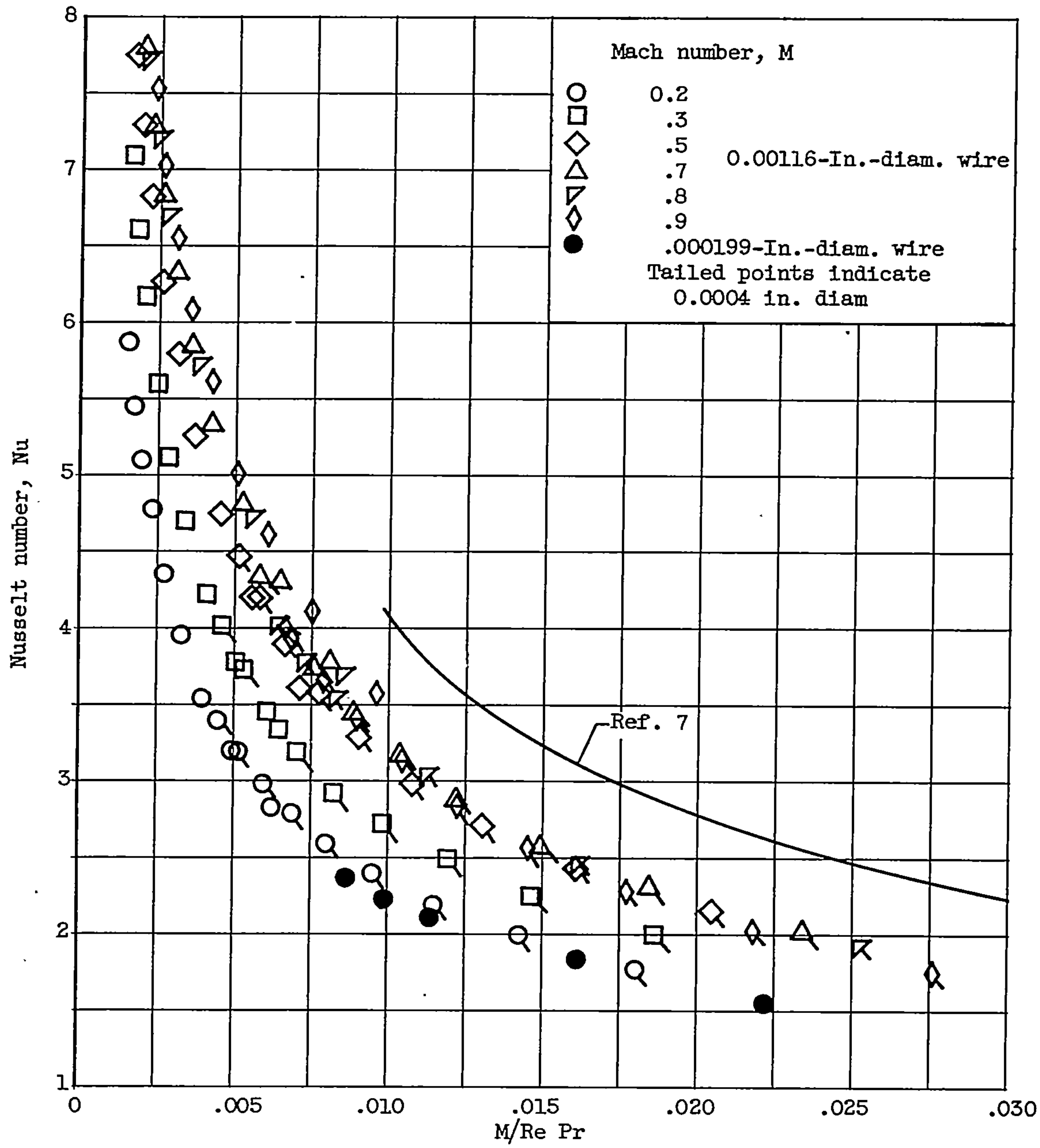

Figure 8. - Variation of heat loss with special parameter for slip flow as suggested by reference 7.

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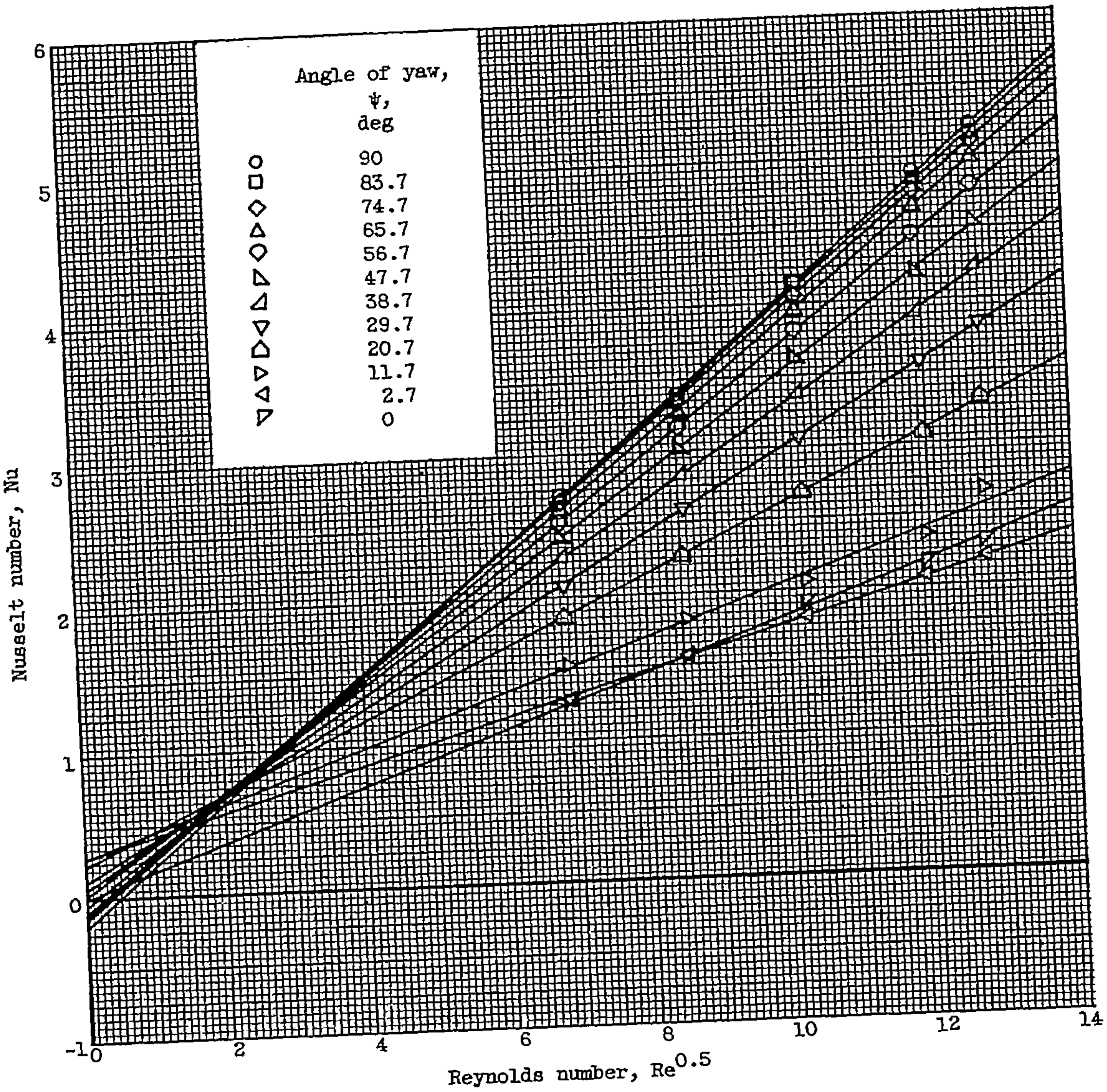

(a) Wire diameter, 0.00116 inch; Mach number, 0.2; thermal conductivity of air, 6.59×10^{-6} Btu per second per foot per °F; coefficient of viscosity, 181×10^{-7} pound per second per foot.

Figure 9. - Variation of heat loss with Reynolds number for various angles of yaw.

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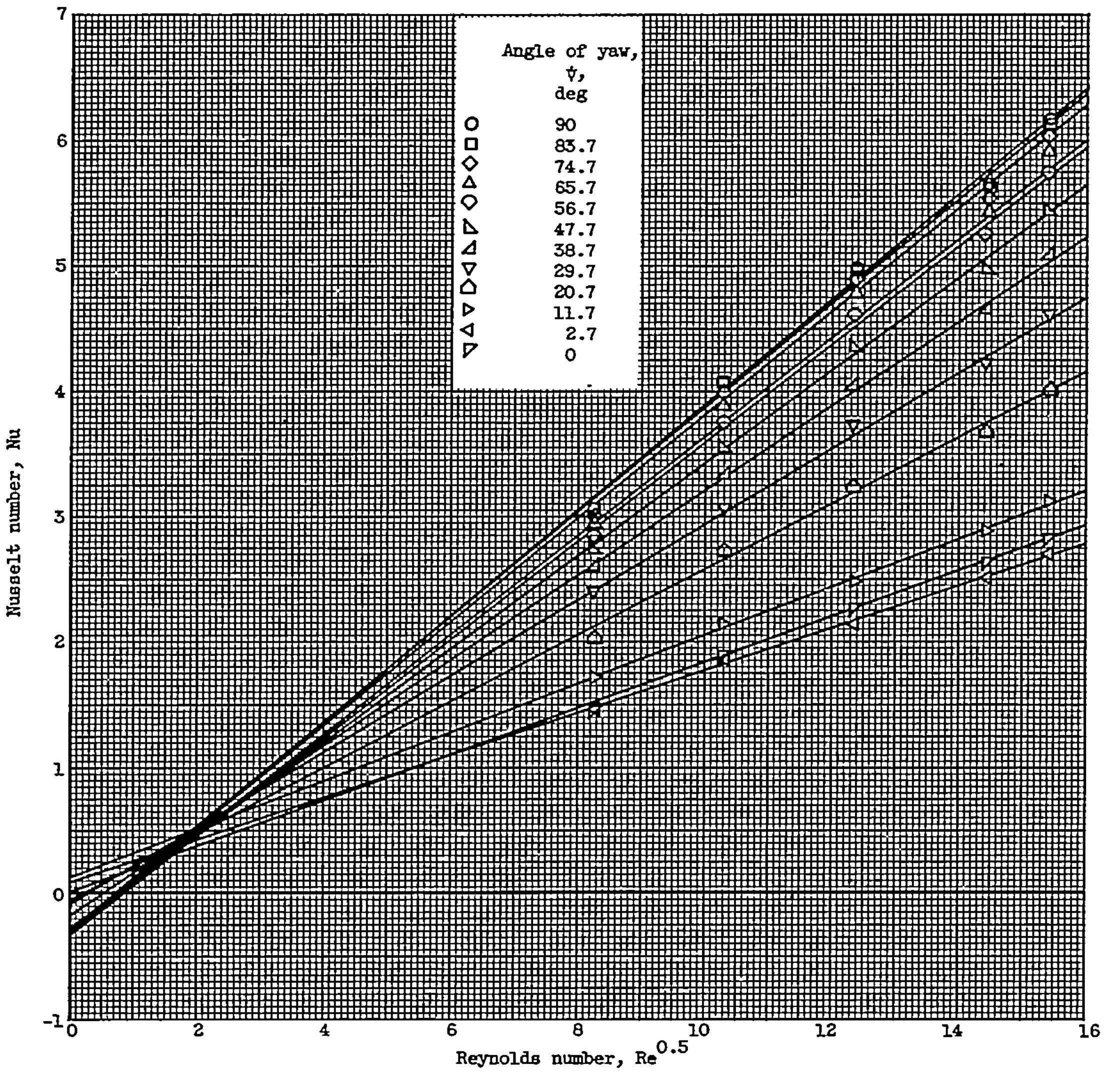
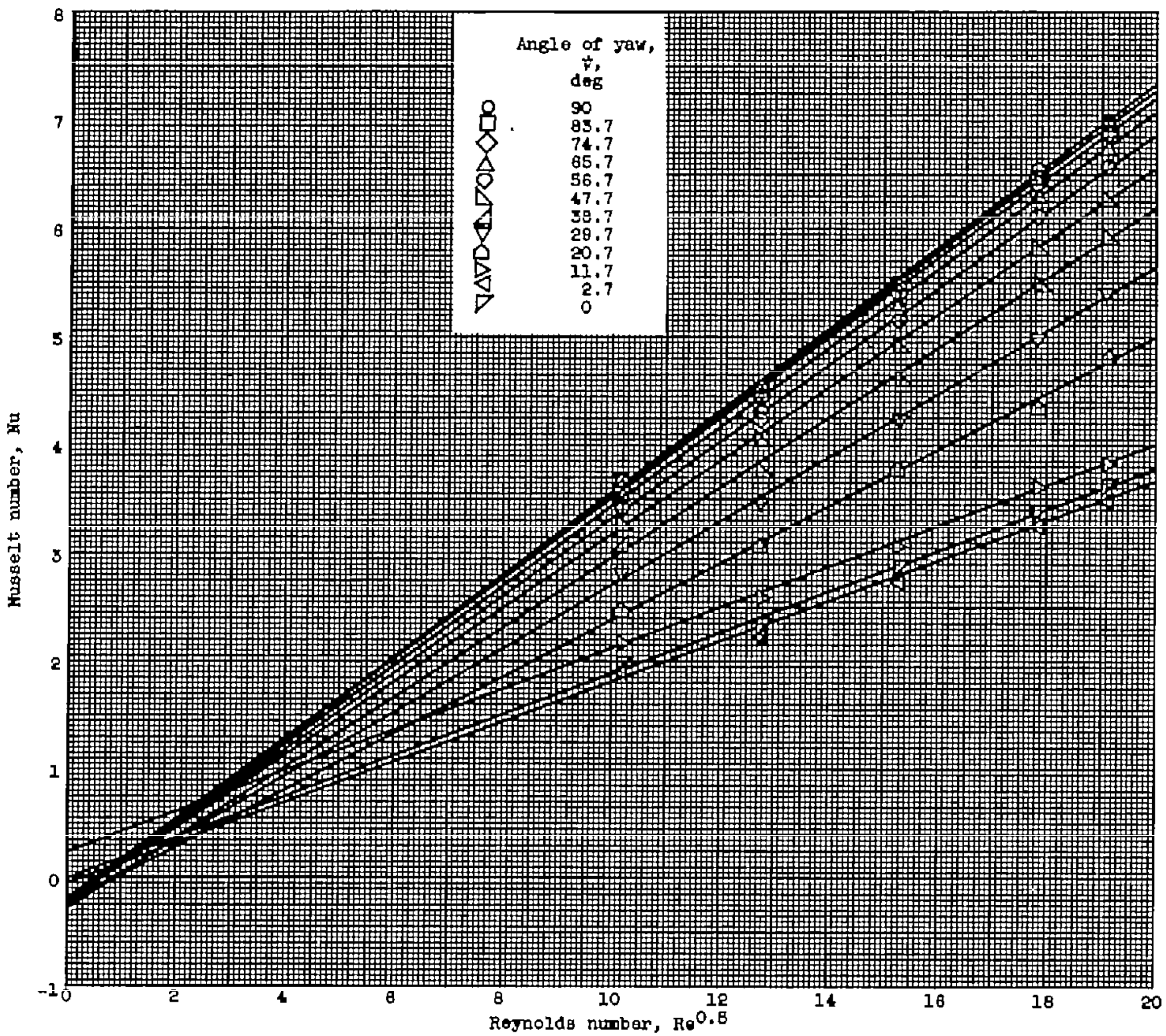


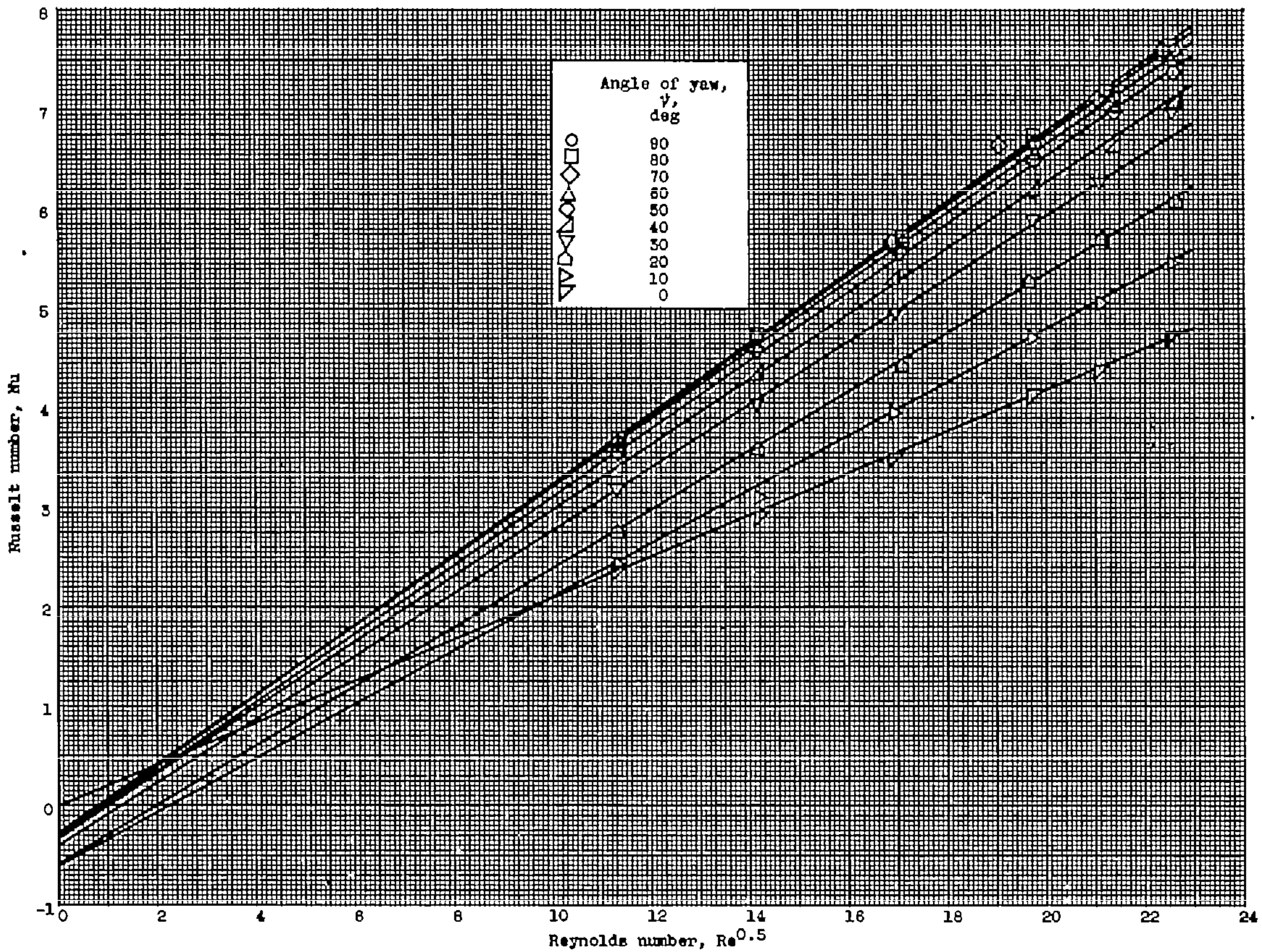
(b) Wire diameter, 0.00116 inch; Mach number, 0.3; thermal conductivity, 6.59×10^{-6} Btu per second per foot per $^{\circ}$F.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



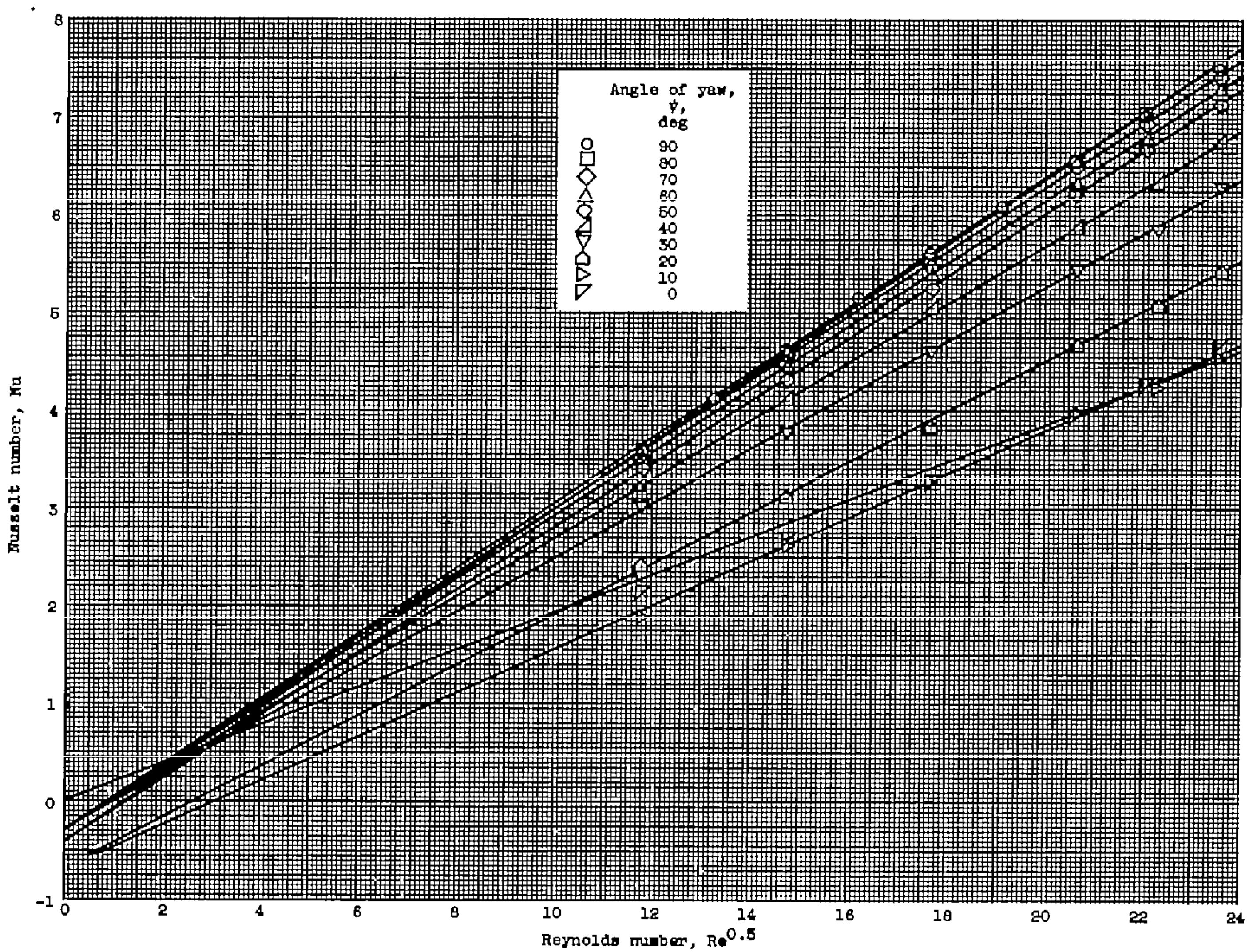
(c) Wire diameter, 0.00118 inch; Mach number, 0.5; thermal conductivity of air, 6.59×10^{-6} Btu per second per foot per °F; coefficient of viscosity, 181×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



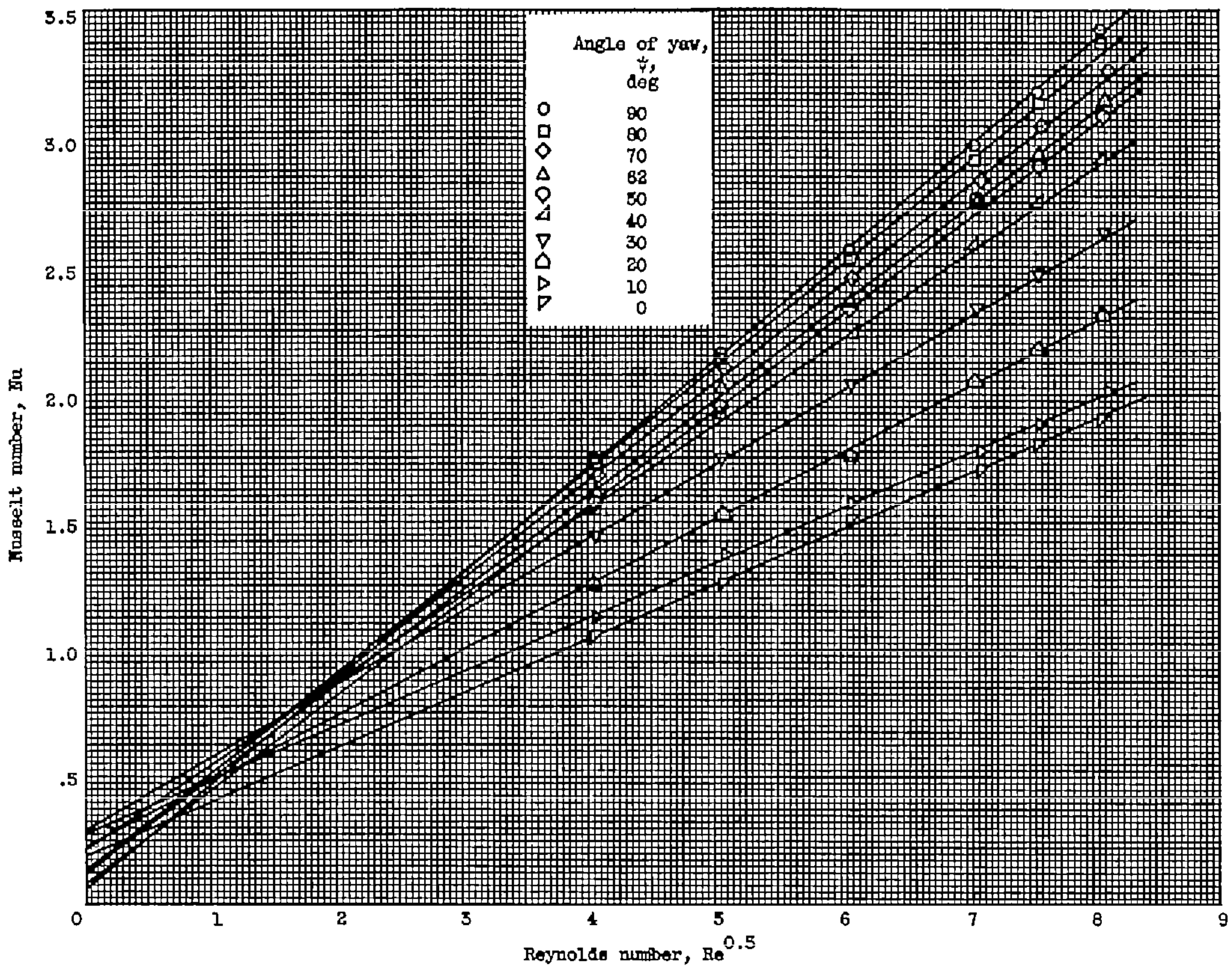
(d) Wire diameter, 0.00116 inch; Mach number, 0.7; thermal conductivity, 6.40×10^{-6} Btu per second per foot per °F; coefficient of viscosity, 17×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



(e) Wire diameter, 0.00118 inch; Mach number, 0.9; thermal conductivity of air, 3.37×10^{-6} Btu per second per foot per $^{\circ}F$; coefficient of viscosity 177×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



(f) Wire diameter, 0.00040 inch; Mach number, 0.2; thermal conductivity of air, 6.47×10^{-6} Btu per second per foot per $^{\circ}$F; coefficient of viscosity, 178×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.

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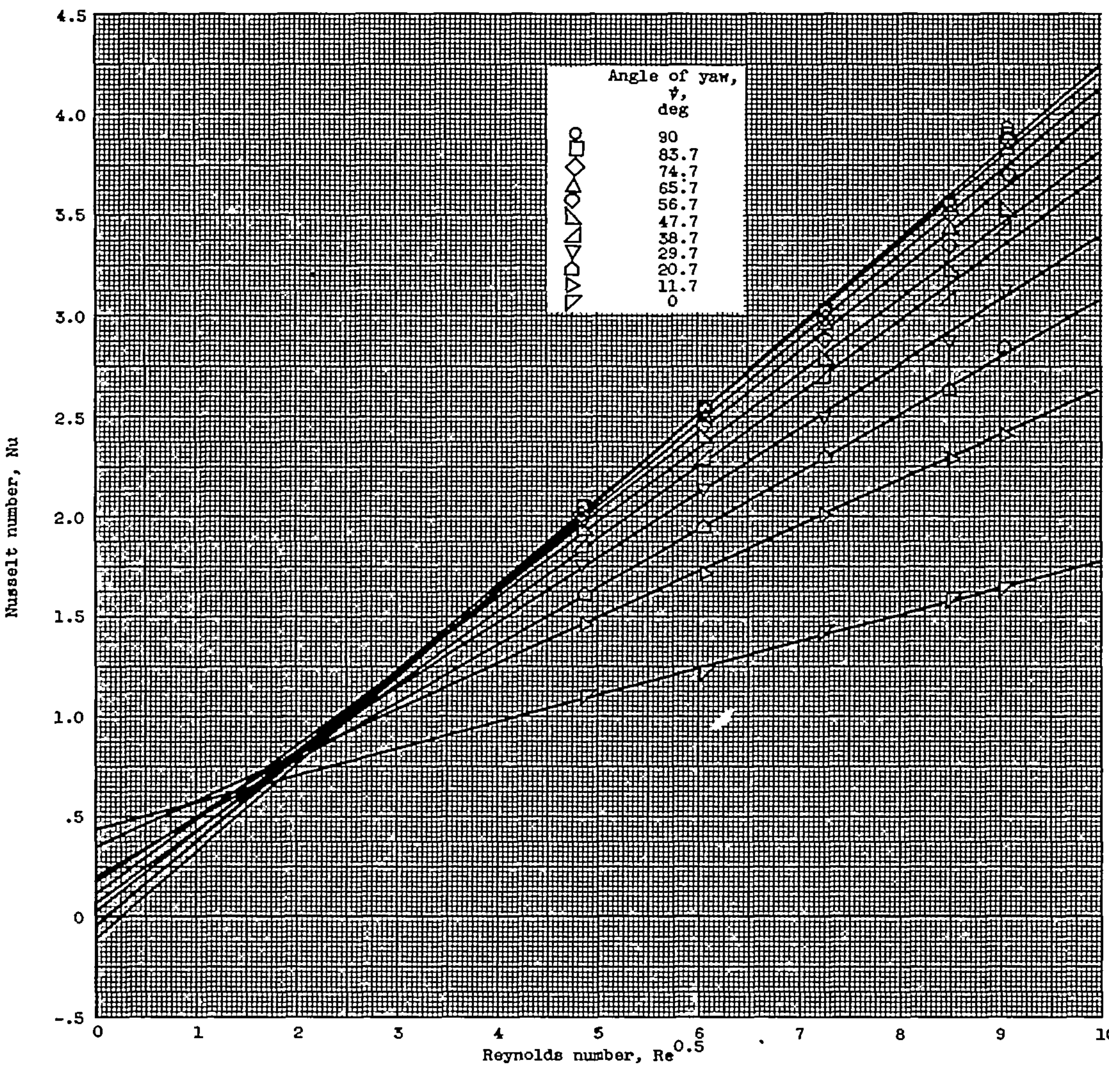
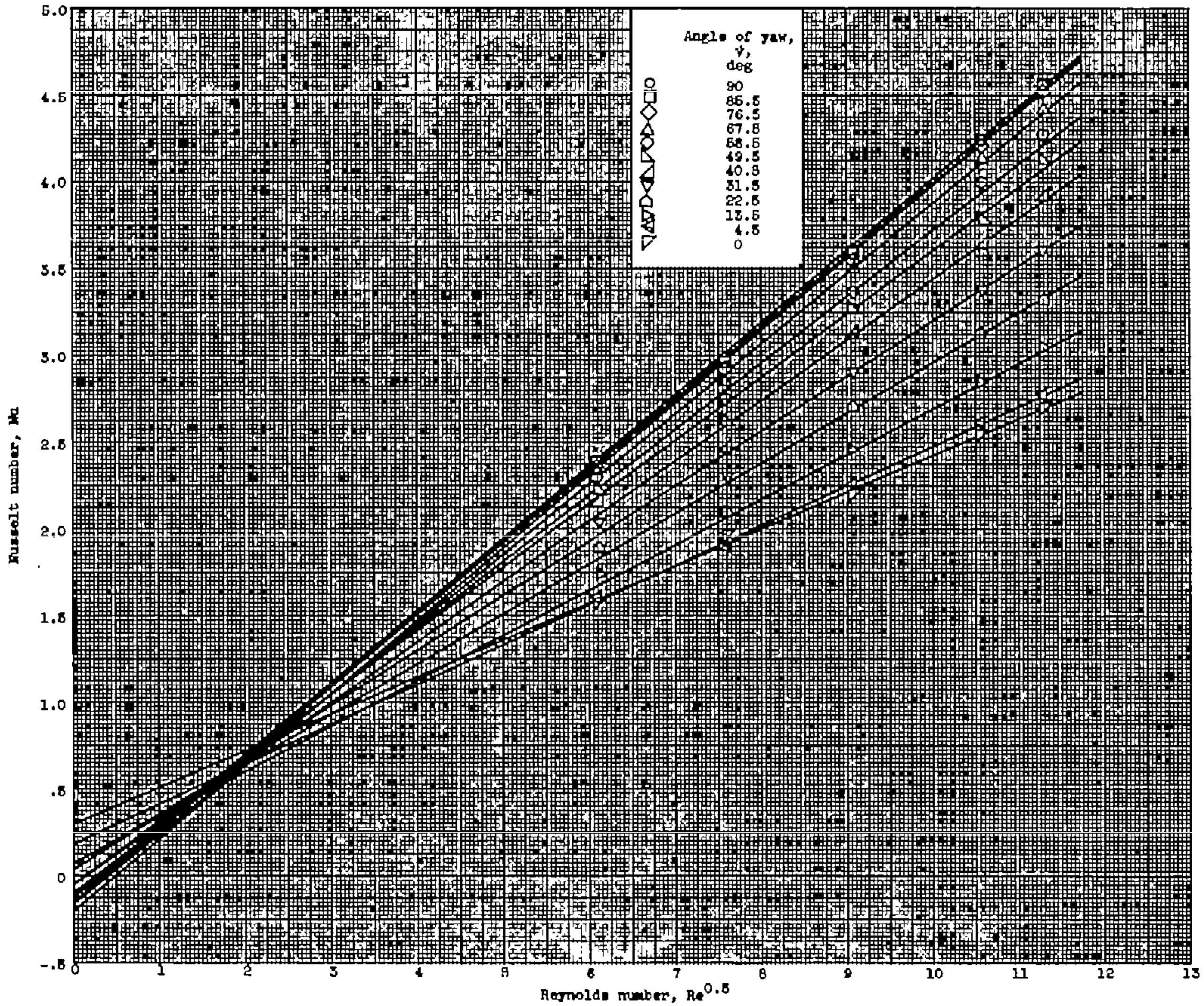


(g) Wire diameter, 0.00040 inch; Mach number, 0.3; thermal conductivity of air, 6.47×10^{-6} Btu per second per foot per °F; coefficient of viscosity, 178×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



(h) Wire diameter, 0.00040 inch; Mach number, 0.5; thermal conductivity of air, 6.40×10^{-6} Btu per second per foot per $^{\circ}$F; coefficient of viscosity, 176×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.

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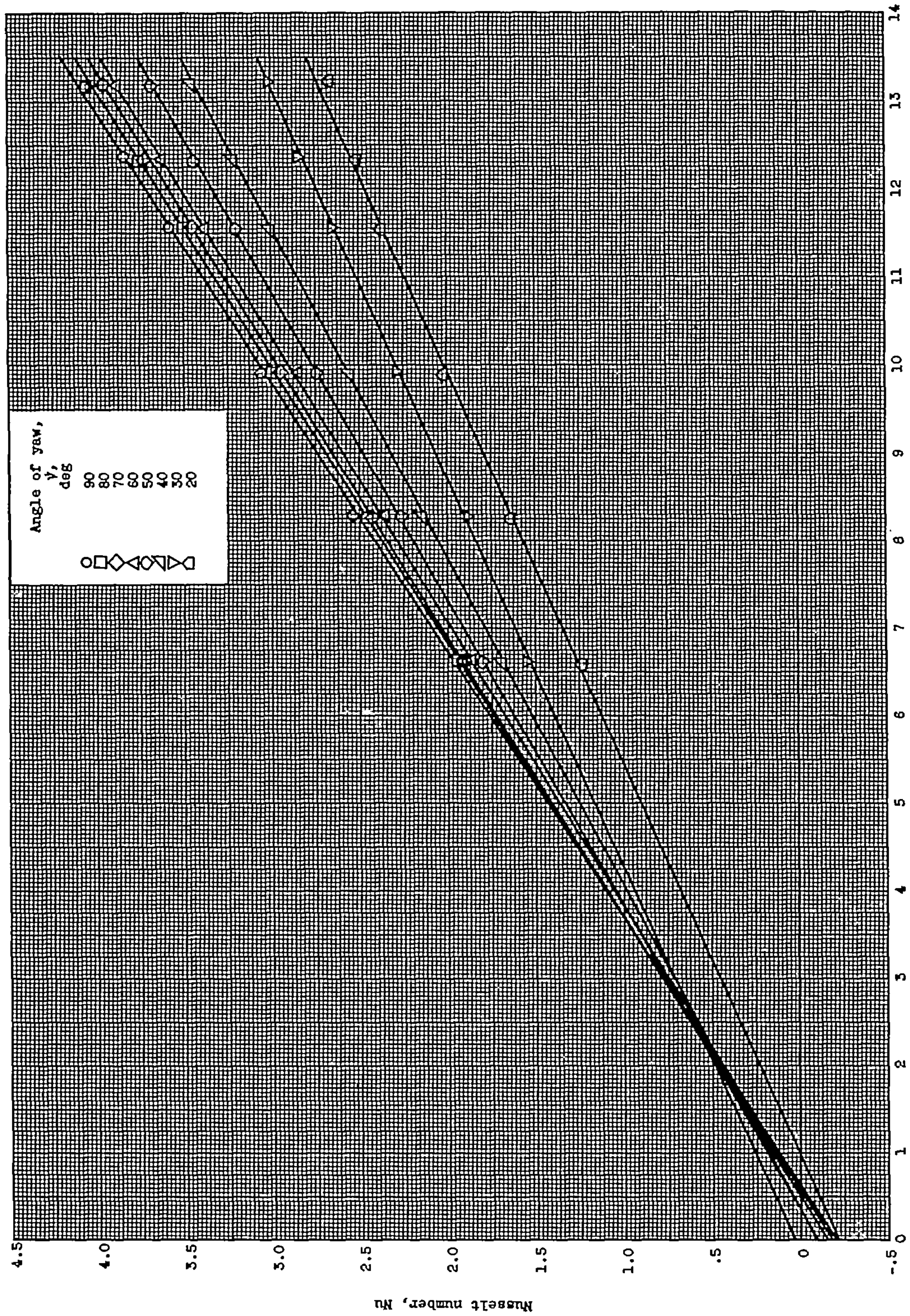
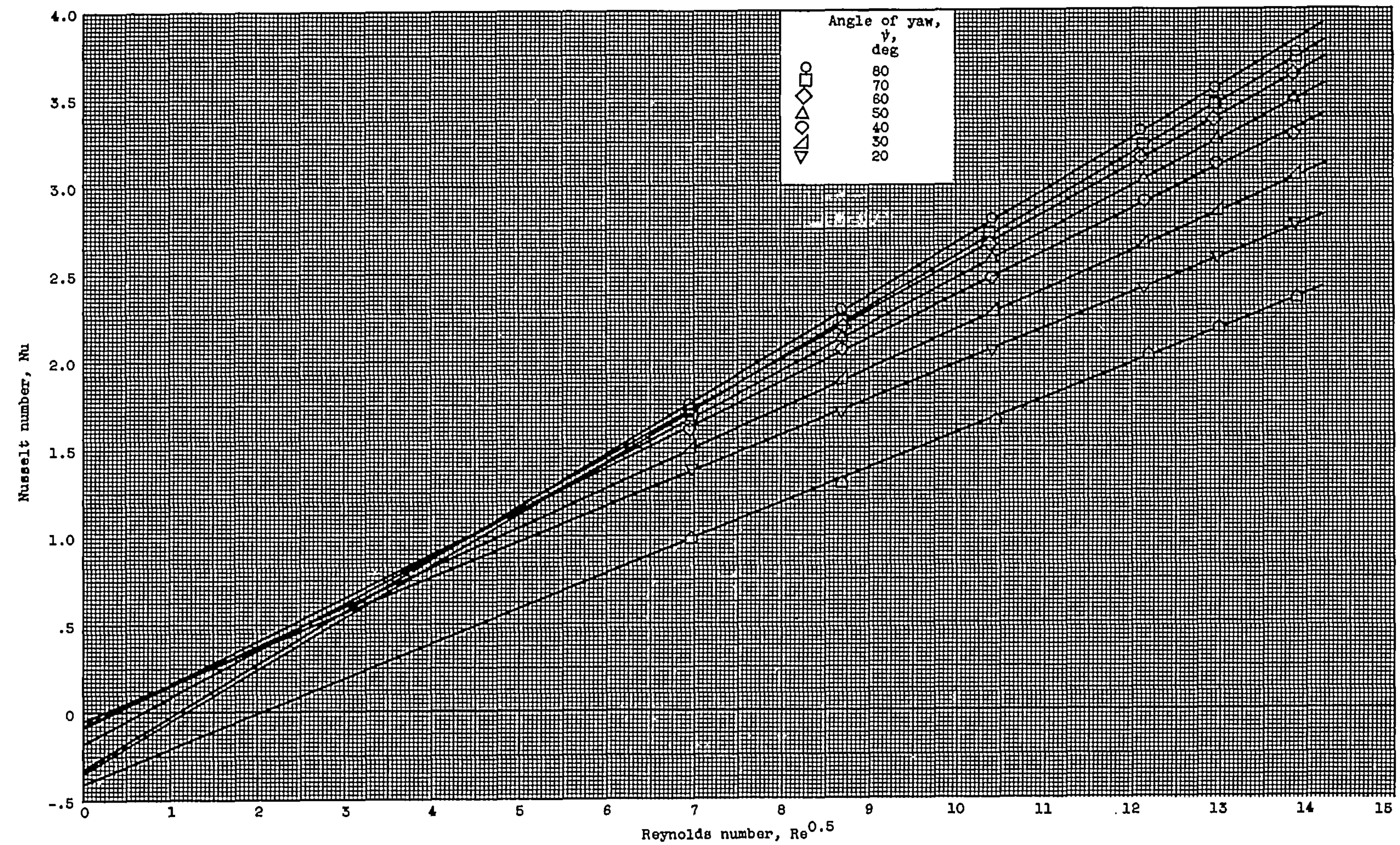
CD-5



(1) Wire diameter, 0.00040 inch; Mach number, 0.7; thermal conductivity of air, 6.49×10^{-6} Btu per second per foot per ^{o}F; coefficient of viscosity, 178×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.



(j) Wire diameter, 0.00040 inch; Mach number, 0.9; thermal conductivity of air, 6.40×10^{-6} Btu per second per foot per °F; coefficient of viscosity, 1.76×10^{-7} pound per second per foot.

Figure 9. - Continued. Variation of heat loss with Reynolds number for various angles of yaw.

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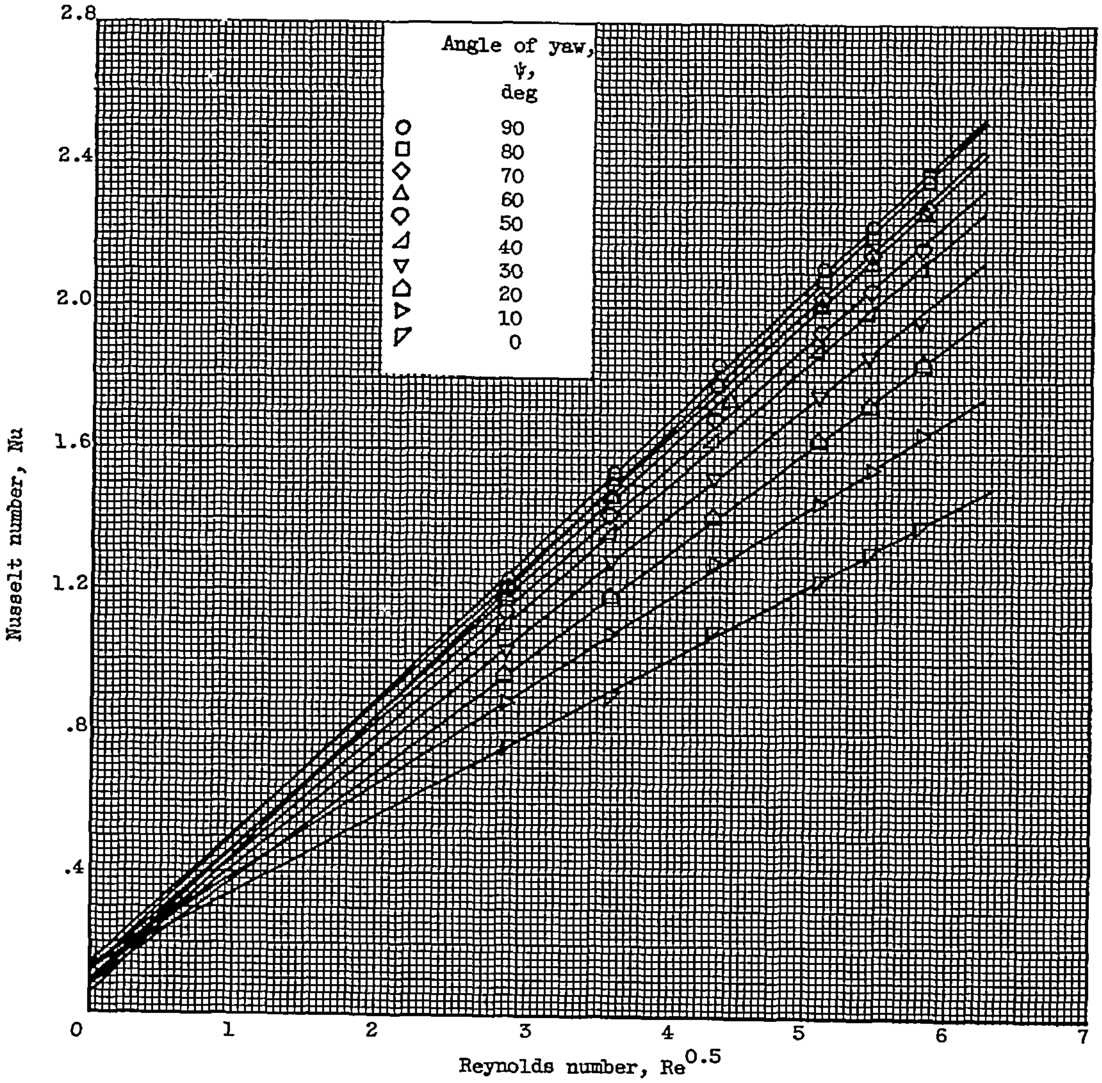
CD-5 back



(k) Wire diameter, 0.000199 inch; Mach number, 0.2; thermal conductivity of air, 6.21×10^{-6} Btu per second per foot per ^{o}F; coefficient of viscosity, 172×10^{-7} pound per second per foot.

Figure 9. - Concluded. Variation of heat loss with Reynolds number for various angles of yaw.

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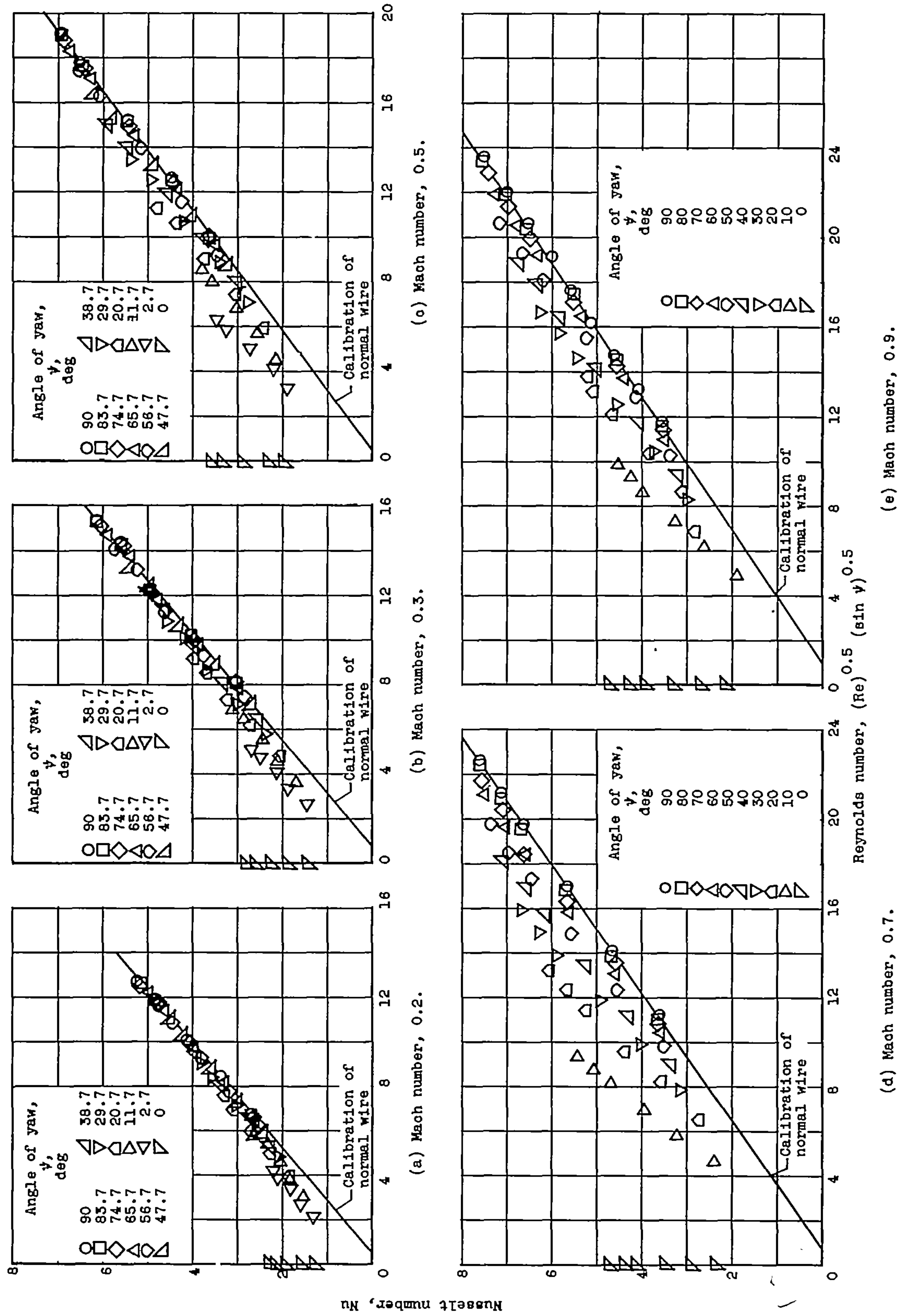

Figure 10. - Variation of heat loss with Reynolds number normal to the flow for wire of 0.00116-inch diameter.

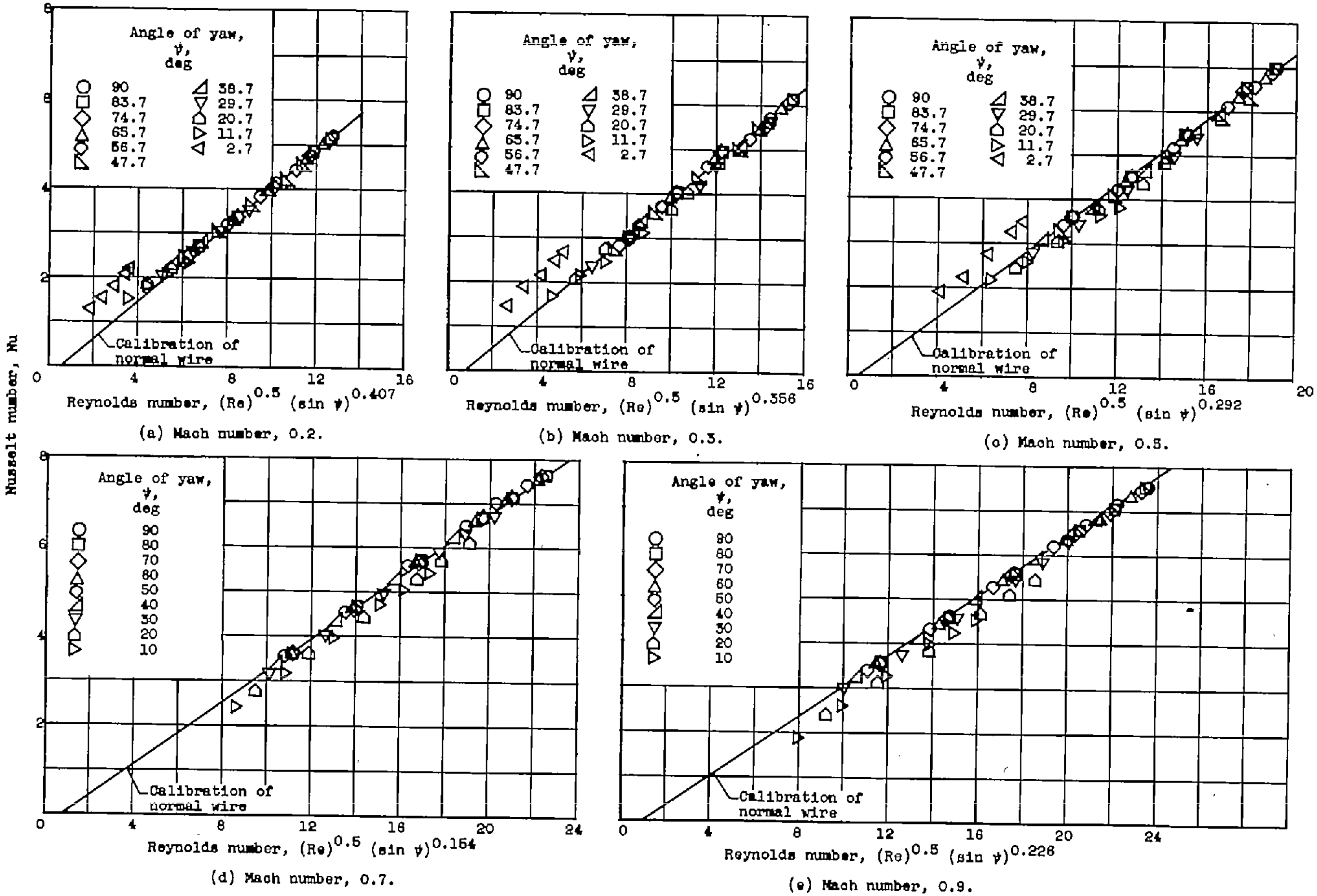

Figure 11. - Variation of heat loss with empirically evaluated angle function, for wire of 0.00116-inch diameter.

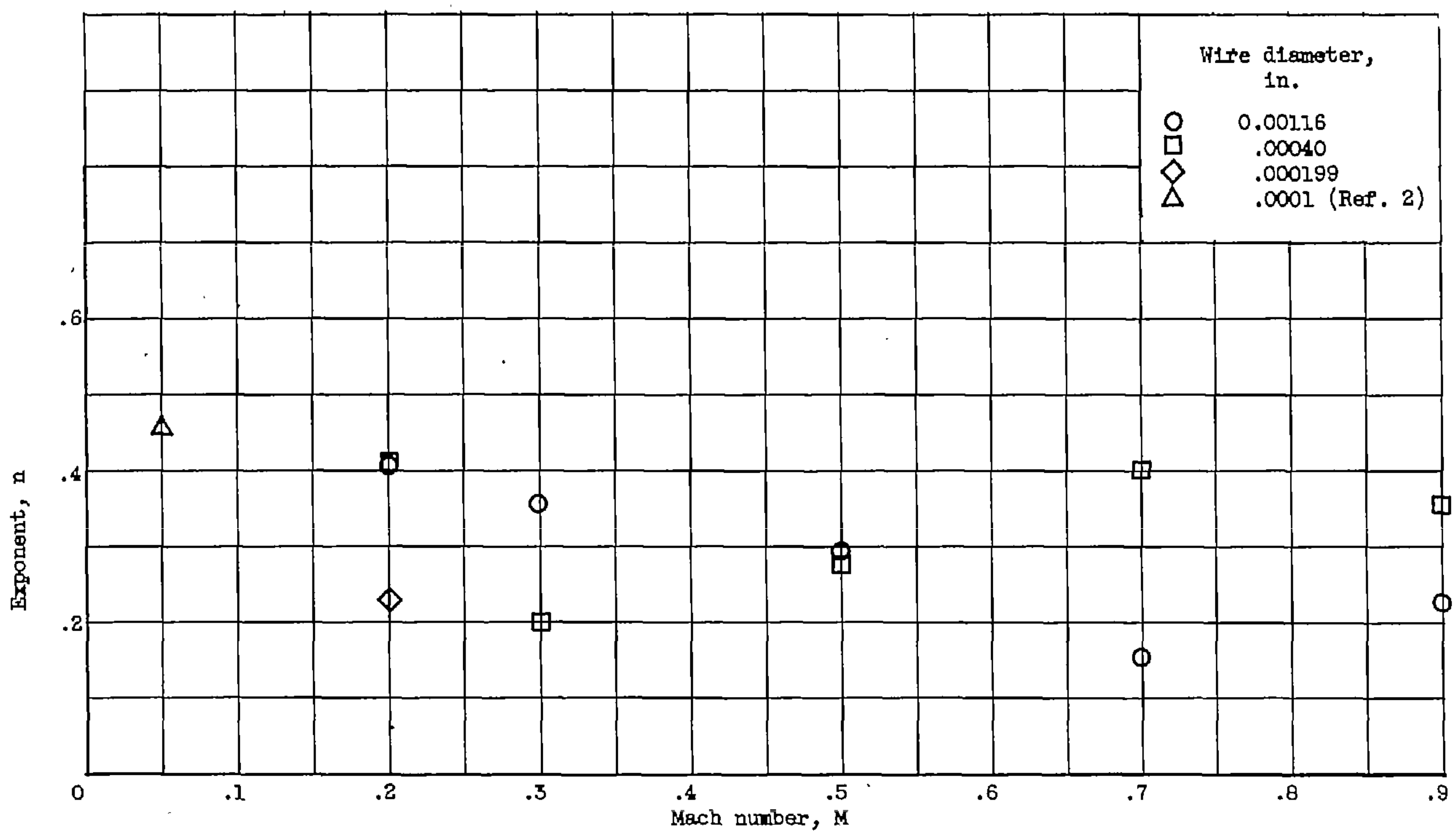

Figure 12. - Summary of variation of exponent n with Mach number and wire diameter.

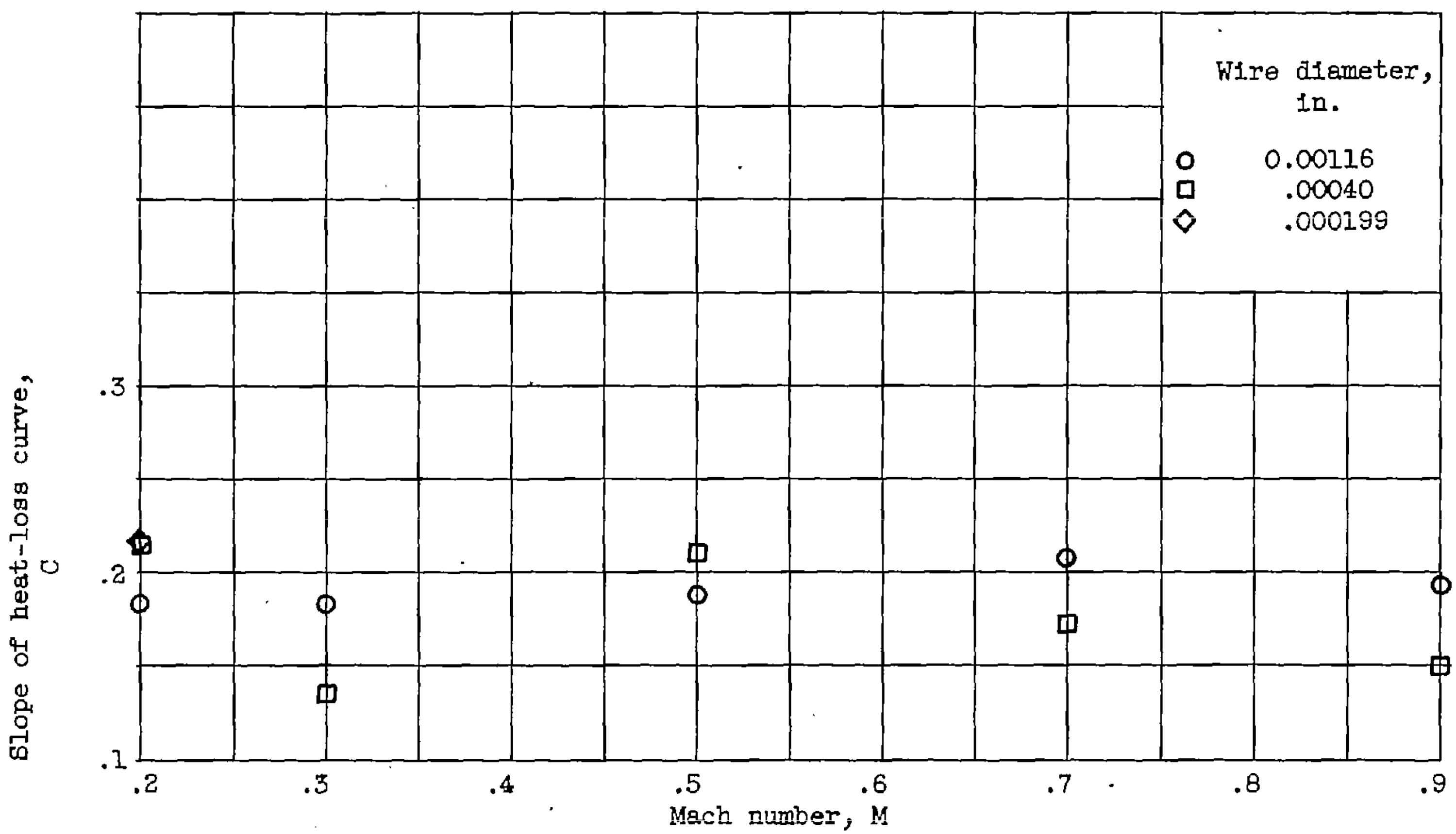

Figure 13. - Summary of variation of slope of heat-loss curves for wires parallel to flow.

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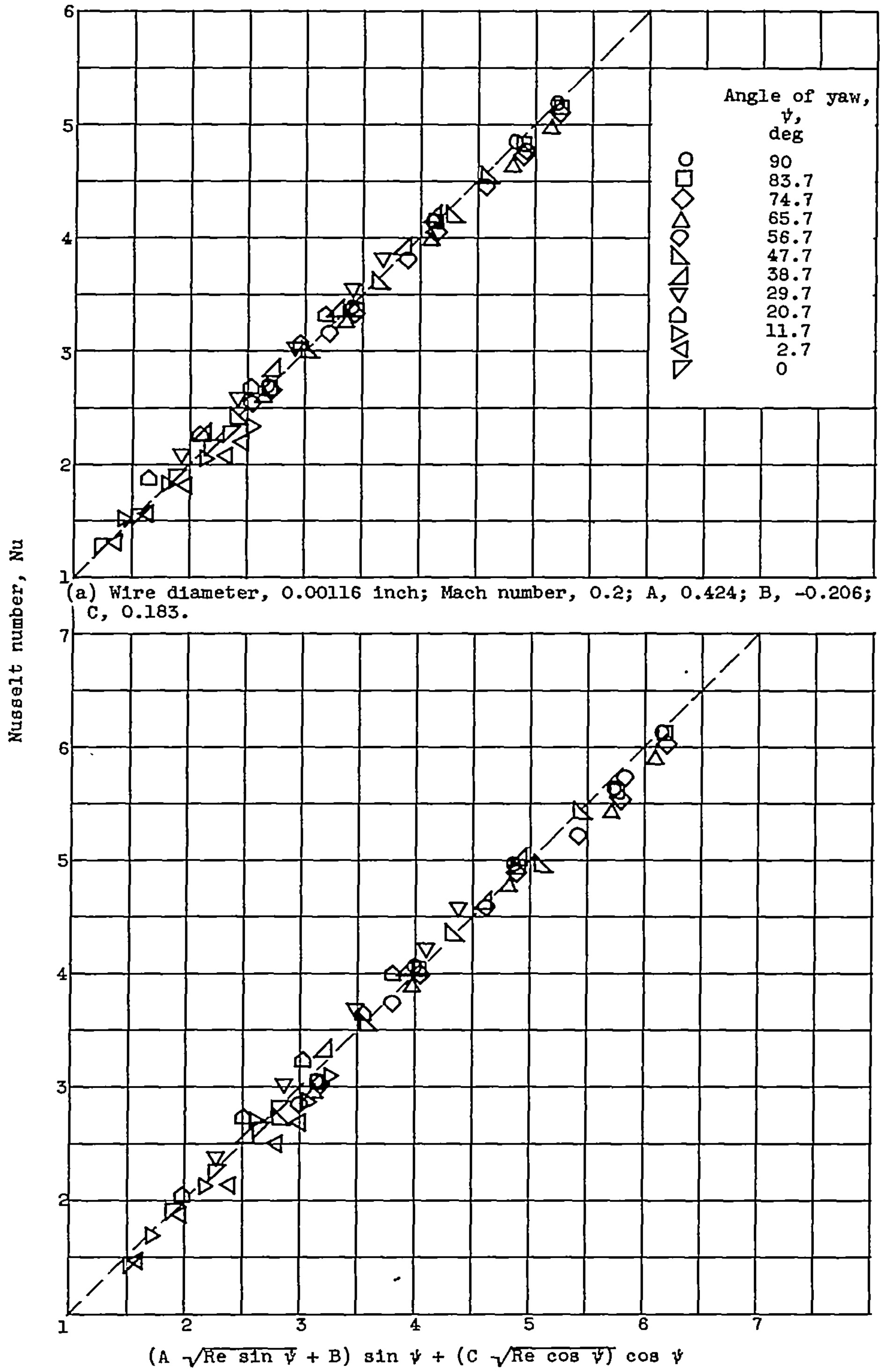

(a) Wire diameter, 0.00116 inch; Mach number, 0.2; A, 0.424; B, -0.206; C, 0.183.

(b) Wire diameter, 0.00116 inch; Mach number, 0.3; A, 0.422; B, -0.338; C, 0.183.

Figure 14. - Correlation of measured heat loss with weighted addition of heat-loss equations for normal and parallel wires according to equation (10).

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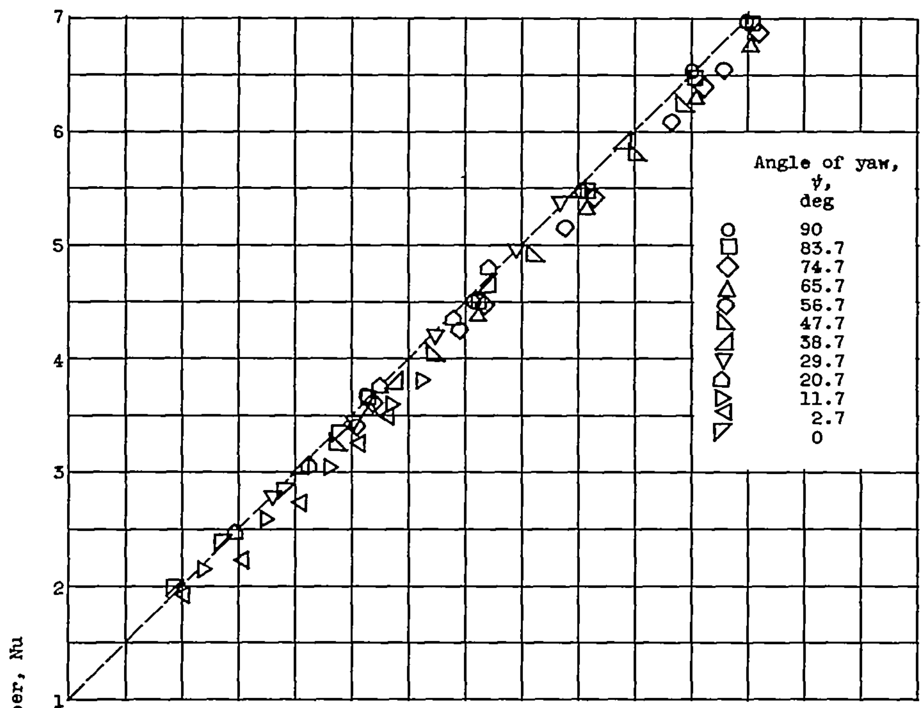
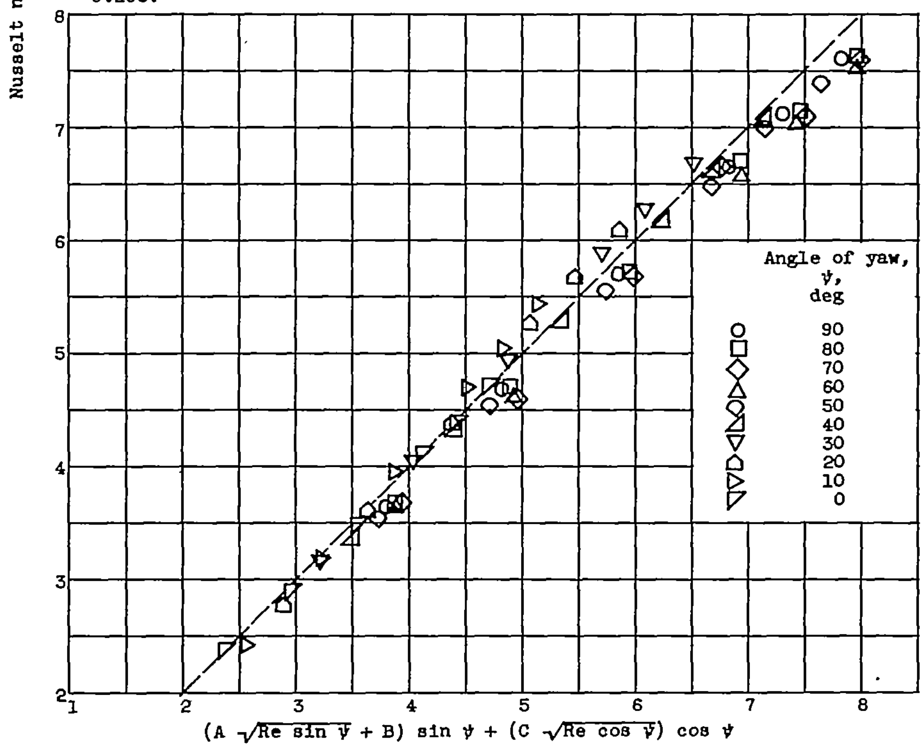
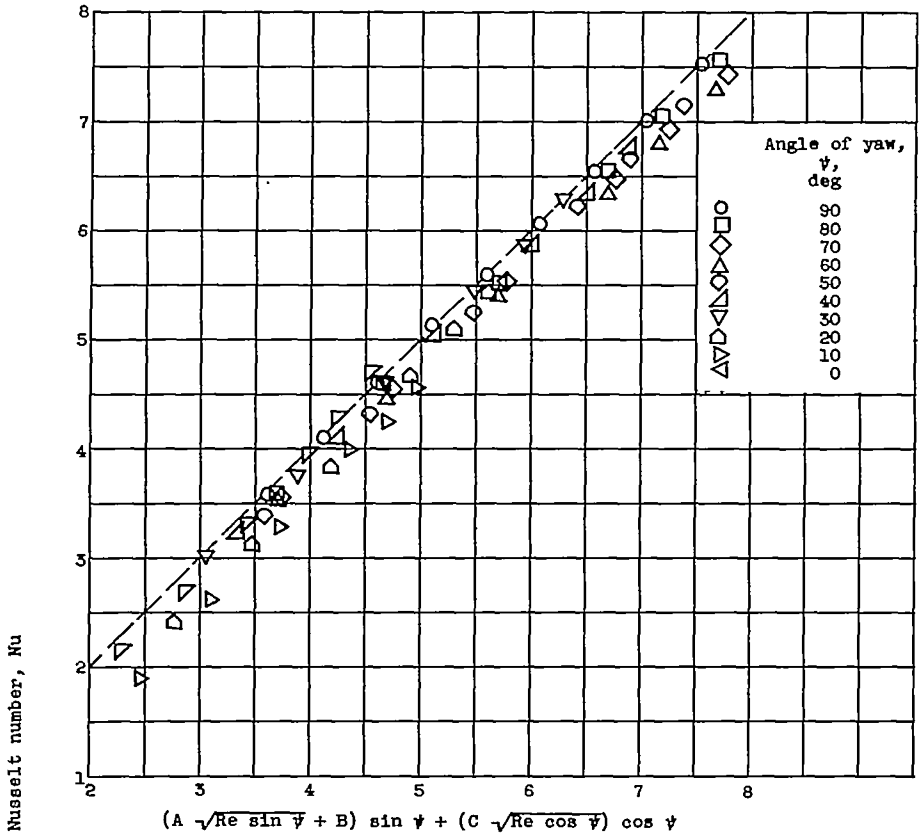


(c) Wire diameter, 0.00116 inch; Mach number, 0.5; A, 0.377; B, -0.214; C, 0.208.

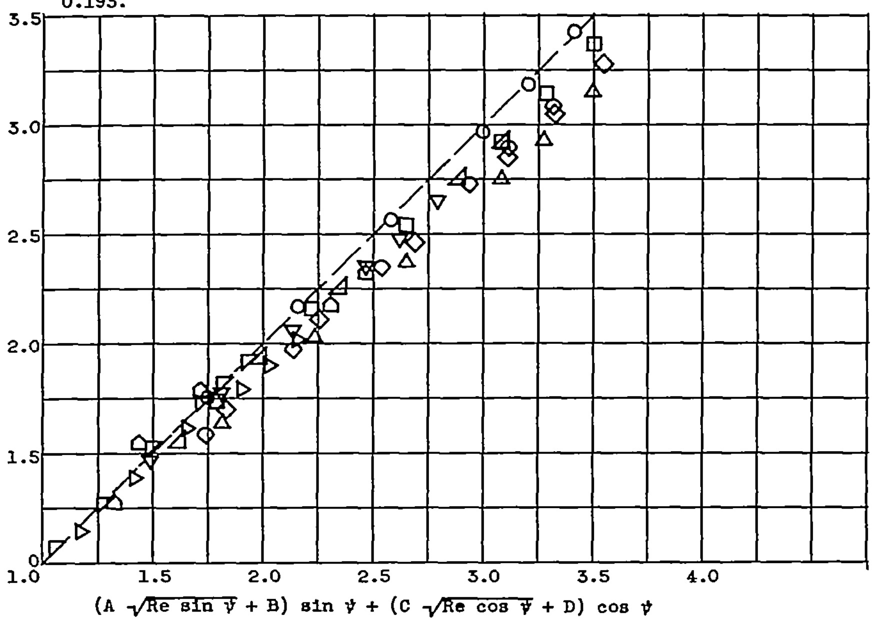


(d) Wi~e diameter, 0.00116 inch; Mach number, 0.7; A, 0.357; B, -0.237; C, 0.208.

Figure 14. - Continued. Correlation of measured heat loss with weighted addition of heat-loss equations for normal and parallel wires according to equation (10).

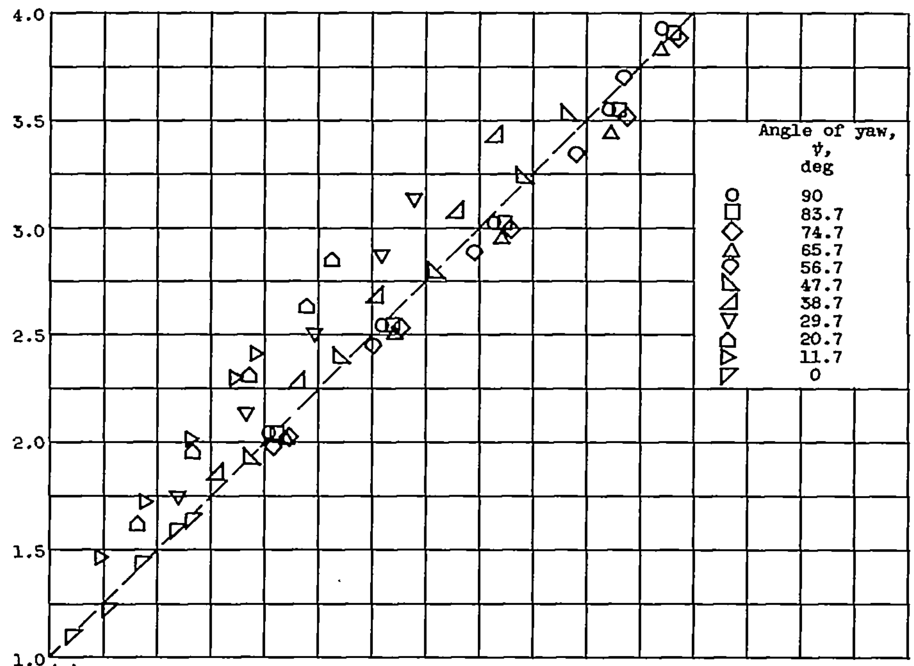


(e) Wire diameter, 0.00116 inch; Mach number, 0.9; A, 0.335; B, -0.322; C, 0.193.

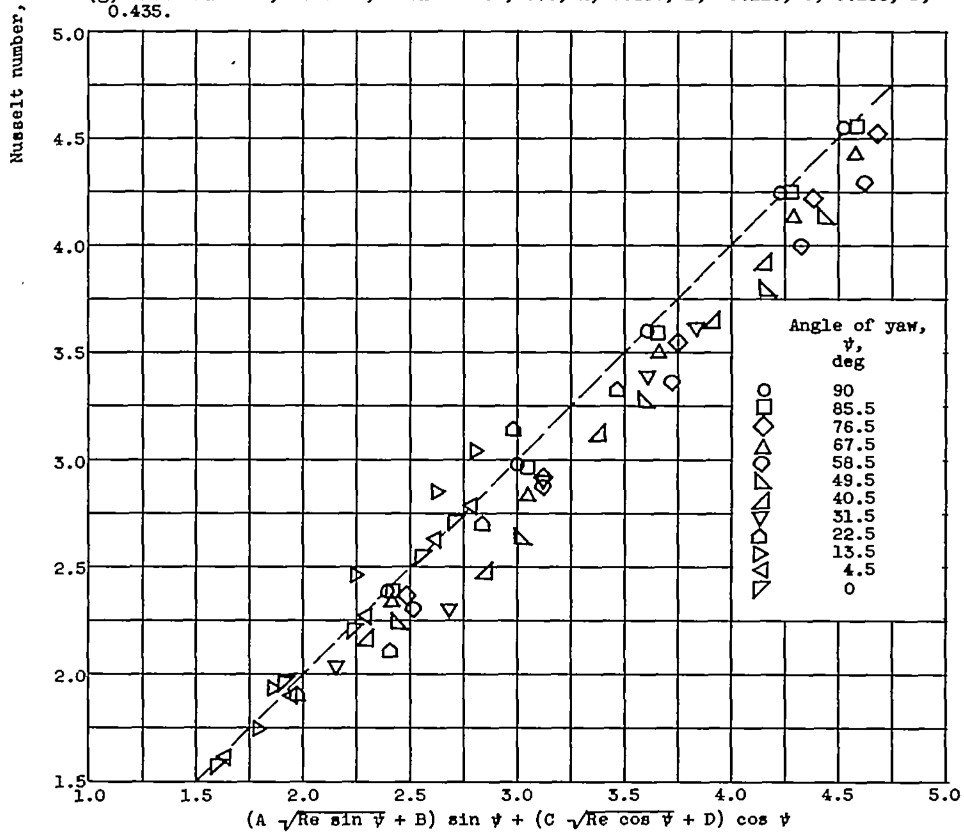


(f) Wire diameter, 0.00040 inch; Mach number, 0.2; A, 0.414; B, 0.0672; C, 0.216; D, 0.186.

Figure 14. - Continued. Correlation of measured heat loss with weighted addition of heat-loss equations for normal and parallel wires according to equation (10).

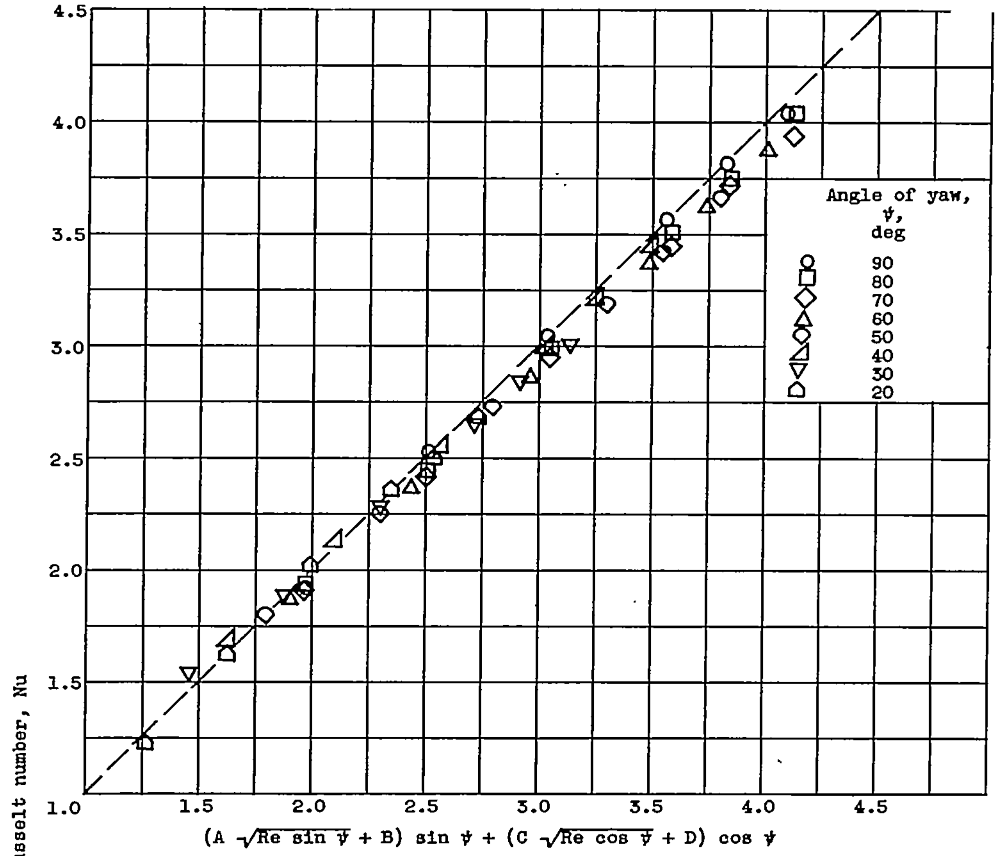


(g) Wire diameter, 0.00040; Mach number, 0.3; A, 0.438; B, -0.113; C, 0.138; D, 0.435.

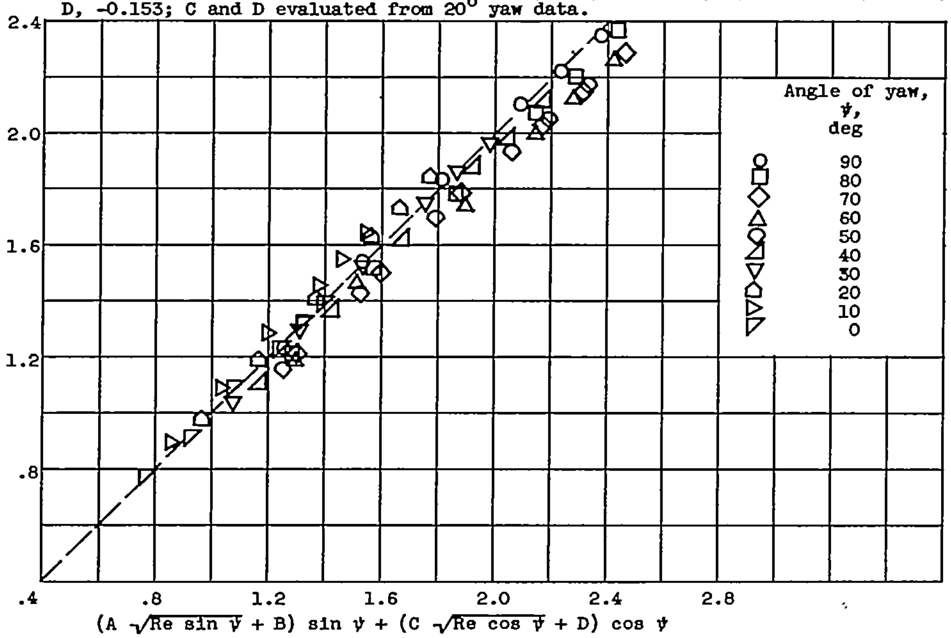


(h) Wire diameter, 0.00040 inch; Mach number, 0.5; A, 0.410; B, -0.0995; C, 0.212; D, 0.305.

Figure 14. - Continued. Correlation of measured heat loss with weighted addition of heat-loss equations for normal and parallel wires according to equation (10).



(i) Wire diameter, 0.00040 inch; Mach number, 0.7; A, 0.325; B, -0.189; C, 0.172; D, -0.153; C and D evaluated from 20° yaw data.



(j) Wire diameter, 0.000199 inch; Mach number, 0.2; A, 0.386; B, 0.119; C, 0.217; D, 0.130.

Figure 14. - Concluded. Correlation of measured heat loss with weighted addition of heat-loss equations for normal and parallel wires according to equation (10).

NACA - Langley Field, Va.